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SECRETARY



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PREFACE.

THE present volume of the *Journal of the Iron and Steel Institute* contains the report of the proceedings at the Annual Meeting of the Institute, held in London in May 1921, together with the papers presented at that Meeting and the discussion and correspondence thereon. An important alteration in the Bye-Laws of the Institute was also given effect to at the Meeting.

For lack of space it has been found necessary to postpone the publication of the usual obituary giving particulars respecting the careers of members of the Institute who died during the year, the list of whose names will be found recorded in the Report of Council.

Section II. contains, as usual, Notes on the Progress of the Home and Foreign Iron and Steel Industries, as reported in the proceedings of Scientific and Technical Societies, and in the Technical Press, together with a Bibliography of the principal works dealing with the metallurgy of iron and steel, mining and allied subjects which have appeared during the past six months.

28 VICTORIA STREET, LONDON, S.W. 1.

July 30, 1921.

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THE IRON AND STEEL INSTITUTE.

SECTION I. *MINUTES OF PROCEEDINGS.*

ANNUAL MEETING, 1921.

THE ANNUAL MEETING of the IRON AND STEEL INSTITUTE was held at the Institution of Civil Engineers, Great George Street, Westminster, S.W., on Thursday and Friday, May 5 and 6, 1921, Dr. J. E. STEAD, F.R.S., President, occupying the Chair.

The Minutes of the last General Meeting, held at the South Wales Institute of Engineers, Cardiff, on September 21 and 22, 1920, were taken as read and signed as a correct record.

SCRUTINEERS.

Messrs. C. A. Ablett (Cardiff) and J. H. Whiteley (Saltburn) were appointed scrutineers of the ballot for the election of new members, and on the conclusion of their scrutiny they announced that the following seventy-nine candidates for membership and eighteen candidates for associateship had been duly elected :

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Marples, Norman Chis- holm	Dallah, Hunton Hill, Erdington, Birming- ham	T. Turner, T. Vickers, A. R. Page.
Rees, Gwilyn	Crwys Farm, Three Crosses, Dunvant, Swansea	J. C. Godsell, J. E. Tor- bock, S. R. Isaac.
Ridgwell, John Leslie	50 Manselton Road, Man- selton, Swansea	J. C. Godsell, S. R. Isaac, H. I. Coe.
Salmon, Llyfnwy Thomas	Brynewel, Plasycod Rd., Morriston, Glam.	H. I. Coe, J. C. Godsell, W. L. Knoyle.
Sheel, Edgar William	Rillington, Cambridge Road, S. Farnborough	H. Sutton, C. W. George, W. H. Dyson.
Turner, Thomas Henry, B.Sc.	8 Albert Road, Heaton Moor, Stockport	T. Turner, J. E. Stead, O. F. Hudson.
Venables, Leslie Goward	"Ty-Dewi," Old Road, Neath, Glam.	S. R. Isaac, J. C. Godsell, H. I. Coe.
Wright, Gerald Spyvee	2 Wharcliffe Villas, Sunny Bank, Sheffield	C. H. Desch, F. C. Thompson, W. J. Gard- ner.

The following seven Associates have been transferred to full membership :

Hammond, David William.
Jackson, Stanley Alexander.
Kayser, John Ferdinand.
Lewis, John Samuel.

O'Neill, Hugh.
Seal, Leonard.
Venters, John Augustus

The SECRETARY read the Report of the Council for 1920, which will be found on p. 11.

STATEMENT OF ACCOUNTS.

Mr. ILLTYD WILLIAMS, Hon. Treasurer, in presenting the Statement of Accounts and Balance Sheet for the past year, said that, notwithstanding the increased expenditure in 1920 as compared with 1919, there was, for the first time since 1917, a surplus.

The accounts showed an excess of income over expenditure amounting to £797, which made good a little over one-half of the losses incurred in the two previous years. The improved position had mainly resulted from the appeal, issued to the members at the beginning of 1920, voluntarily to double their annual subscription. As stated in their Report, the Council desired to extend their warm thanks to all those who had so generously contributed. Another satisfactory item was the increased revenue from Journal sales (£809 as compared with £341 in 1914). The cost of printing and publishing the Journal had so much increased that the old price involved a loss, and in 1919 it was decided to increase the charges. The fact that, notwithstanding that increase, the number of sales had steadily risen afforded gratifying testimony to the appreciation in which the Institute's proceedings were held.

The expenditure side of the account showed that the library expenses had more than doubled. During the war years they had no option, and were obliged to allow that work to get into arrear, and an effort had been made to correct that state of affairs in some measure. The Autumn Meeting expenses were considerably higher, and the cost of the Annual Meeting was also somewhat higher; but it was very satisfactory to note that the total cost of producing the Journal, stationery, and printing was practically the same as for 1919, notwithstanding that, during the year, all printing charges were subject to a further increase. That increase was slightly off-set by a slight fall in the value of paper, but mainly by economy realised by purchasing the paper direct, a circumstance for which he thought Mr. Lloyd should receive the credit.

At the Autumn Meeting he had, to his regret, to inform the members that the old rate of the annual subscription was no longer sufficient to meet the needs of the Institute, and by the authority of the Council he had given formal notice of a resolution, to be submitted immediately to the present meeting, by which it was proposed to raise the annual subscription from £2 2s. 0d. to £3 3s. 0d. for members in the United Kingdom and to £2 12s. 6d. for members resident abroad, to alter the terms for life composition, and to make an alteration in the first part of Rule 22. As the proposal had met with no opposition of any kind,

the Council had acted in anticipation of the adoption of the resolution by the present meeting, and had requested members to be so kind as to pay their subscriptions on the new proposed scale as from the commencement of the present year.

Since January 1, 1912 members had forwarded their subscriptions, and of those 1225 had paid at the new rate and 87 at the old rate. Nearly all the latter were amongst those who had a standing order lodged with their bankers, and it was no doubt merely inadvertence on their part that they had omitted so far to revise their instructions to their bankers.

The PRESIDENT then formally moved the adoption of the Annual Report and Statement of Accounts (see pp. 11-26), the motion being carried unanimously.

ALTERATIONS OF BYE-LAWS 21 AND 22, RELATING TO ANNUAL SUBSCRIPTIONS.

Mr. ILLTYD WILLIAMS, Hon. Treasurer, moved the following resolutions, formal notice of which had been given at the Autumn Meeting held at Cardiff on September 21, 1920, for the alteration of Bye-laws 21 and 22, relating to the annual subscriptions and life composition fees :

That Bye-law 21 as at present existing be revoked, and that in substitution thereof the following be inserted :

“ Every member shall on election pay an entrance fee of £2 2s. 0d.

“ A member resident in the United Kingdom shall pay an annual subscription of £3 3s. 0d.

“ A member resident outside of the United Kingdom shall pay an annual subscription of £2 12s. 6d.

“ Any member whose subscription is not in arrear may at any time before the 30th June in any year, or, if elected after that date in the year, within one month of his election, compound for his subscription for subsequent years on payment according to the following scale :

Up to 29 years of age	50 guineas.
From 30 to 39 „	45 „
„ 40 to 49 „	40 „
„ 50 to 59 „	35 „
„ 60 and upwards	30 „

That Bye-law 22 be amended as follows :

“The annual subscription shall be payable in advance on January 1st in each year, or in the case of members newly elected within one month of such election. Members who are elected at a general meeting in the autumn in any year shall pay only half the subscription for that year. Any member whose subscription shall be twelve months in arrear shall forfeit all the privileges of the Institute; and the Council, after having given due notice, in the Form ‘D’ in the Appendix, shall be empowered to remove such name from the lists of the Institute.”

Sir ROBERT HADFIELD, Bart., Past-President, seconded the motion, which was carried unanimously.

CARNEGIE SCHOLARSHIP AWARDS.

The SECRETARY announced the following awards of grants from the Carnegie Research Fund :

Dr. L. AITCHISON, Birmingham, £100 to assist him in carrying out an investigation of the low apparent elastic limit in quenched and work-hardened steels, with particular reference to fatigue strength, proof stress, and constitution.

Professor C. O. BANNISTER and Mr. A. E. FINDLEY, Liverpool, £100 jointly to enable them to investigate the mechanical properties and heat treatment of very low carbon high chromium steels.

Mr. F. C. LANGENBERG, of Watertown Arsenal, United States, £100 for the purpose of carrying out a research on impact testing.

Mr. J. N. GREENWOOD, Sheffield, £50 to carry out a research with a view to obtaining optical data on steels and steel-making materials to enable corrections to be made to temperature measurements of molten steel taken with an optical pyrometer.

The following papers were read and discussed at the meeting :

MAY 5.

“The Welding of Steel in Relation to the Occurrence of Pipe, Blow-holes, and Segregates in Ingots,” by H. BREARLEY.

“Solid Solution of Oxygen in Iron,” by Dr. J. E. STEAD, F.R.S.

“The Scientific Control of Combustion,” by H. T. RINGROSE.

“Notes on the Cleaning of Blast-Furnace Gas,” by S. H. FOWLES.

“Blast-Furnace and Cupola Slags: their Composition and Graphic Methods for Determining their Constitution,” by J. E. FLETCHER.

MAY 6.

- “The Prevention of Hardening Cracks, and the Effect of Controlling the Recalescence in a Tungsten Tool Steel,” by S. N. BRAYSHAW.
“On the Cause of Quenching Cracks,” by K. HONDA, T. MATSUSHITA, and S. IDEI.
“Cupric Etching Effects produced by Phosphorus and Oxygen in Iron,” by J. H. WHITELEY.
“Roentgen Spectrographic Investigations of Iron and Steel,” by A. WESTGREN.
“Comparison of Different Methods of Estimating Sulphur in Steel,” by T. E. ROONEY.

The following papers were taken as read :

- “The Protection of Iron with Paint against Atmospheric Corrosion,” by J. NEWTON FRIEND.
“Slip-lines and Twinning in Electro-deposited Iron,” by W. E. HUGHES.

VOTES OF THANKS.

On the motion of the PRESIDENT a hearty vote of thanks was accorded to the Council of the Institution of Civil Engineers for having so generously allowed the Institute the use of their room for the purposes of the Annual Meeting.

Sir ROBERT HADFIELD seconded the motion, which was carried unanimously.

Mr. ALFRED HUTCHINSON proposed a hearty vote of thanks to the President for his able conduct of the proceedings. He said those who had been members of the Institute longest knew with what affection Dr. Stead was regarded by the members, and how important was the work he had done on behalf of the Institute.

The motion having been carried by acclamation, the PRESIDENT briefly thanked the meeting for their appreciation, and the proceedings terminated.

REPORT OF COUNCIL.

THE Council of the Iron and Steel Institute have pleasure in submitting to the members, on the occasion of this, the Fifty-second Annual General Meeting, their Report of the progress and work of the Institute during the year 1920.

ROLL OF THE INSTITUTE.

During the year 180 new members were elected and 12 associates were transferred to full membership. The total membership of the Institute on December 31, 1920, was as follows :

Patron	1
Honorary Members	4
Life Members	80
Ordinary Members	2067
Associates	41
<hr/>	
Total	2193

Resignations were received from sixty-eight members, and the names of fifteen members were removed from the Register for non-payment of their subscriptions.

During the year the deaths of twenty-eight members have been reported, their names being recorded in the following list :

Adamson, J. (Manchester)	August 14.
Ainsworth, G. (Consett, Co. Durham), Vice-President	January 18.
Allen, Col. Sir Charles, V.D. (Sheffield), Member of Council	April 13.
Bamber, H. K. (Addiscombe)	December 4.
Black, T. (Cullercoats)	February 27.
Bowes, F. (Middlesbrough)	June 3.
Cunningham, P. N. (Mossend).	August 17.
Dixon, D. W. (Saltburn-by-the-Sea)	December 16.
Gayley, J. (New York)	February 25.
Harrison, W. K. (Stourbridge) . . . . .	...
Higson, Jacob (Northwood, Middlesex)	November 18.

Jenkins, David (Wishaw)	September 25.
Jenkins, Lewis (Briton Ferry)	November.
Luff, A. E. (Sheffield)	...
Maclaren, C. F. (Lanark)	May.
McNeil, Charles (Glasgow)	November 1.
Marston, S. (Middlesbrough)	January.
Martin, C. Stanley (Manchester)	February.
Mather, Sir William (Manchester)	September 18.
North, Sir Harry (Eltham)	November 26.
Price, John (London)	April 3.
Procter, J. (Halesowen)	March 6.
Sissons, J. W. (Sheffield)	June.
Steel, Henry (Sheffield)	October 7.
Thomas, A. S. (Cardiff)	July 12.
Turner, H. G. (London)	February 15.
Whitton, F. H. (Hamilton, Ont.)	October 24.
Winder, B. W. (Sheffield)	July 19.

The deaths of the following ten members occurred prior to 1920, but were not noted in the Report of Council last year :

Andersson, O. (Atrafors, Sweden)	October 20, 1918.
Davy, W. A. (Burry Port, Carm.)	1919.
Esteban, A. (Trubia, Spain)	May, 1918.
Firmstone, F. (Easton, Pa., U.S.A.)	June 27, 1917.
Goujon, Jules (Moscow)	1919 (?).
Holtzer, Marcel (Unieux, France)	...
Roebeling, C. J. (New Jersey, U.S.A.)	October 5, 1918.
St. Oswald, Lord (Wakefield)	April 13, 1919.
Shanks, Col. W. (Johnstone, N.B.)	July 29, 1919.
Teather, J. (Southport)	September 6, 1919.

The Council have very sincerely to deplore the death of their Senior Vice-President, Mr. George Ainsworth, who was a loyal supporter of the Institute and a most constant attendant at its meetings. The Council have likewise deeply to regret the death of Colonel Sir Charles Allen, Member of Council.

HONOURS CONFERRED UPON MEMBERS OF THE INSTITUTE.

The Council desire to place on record their congratulations to several members upon the honours conferred upon them during the year :

Sir William Beardmore, Bart., Past-President, has been raised to the peerage with the title Lord Invernairn of Strathnairn. Mr. J. W. Beynon and Mr. Frederick Mills (Member of Council) have been created baronets; and Colonel W. Charles Wright (Member of Council), Mr. W. S. Abell, and Mr. John Dewrance were created Knight Commanders of the Order of the British Empire. Mr. W. Peter Rylands (Member of Council), Mr. W. B. M. Bird, and Mr. J. H. R. Kennal have had knighthoods conferred upon them. Colonel D. Carnegie, Mr. George Hatton (Member of Council), Mr. A. G. M. Jack, Mr. W. J. Larke, Mr. F. Z. Lloyd, Mr. H. Peile, Mr. C. P. Sandberg, Capt. H. Riall Sankey, and Mr. V. B. Stewart have had conferred upon them Commanderships of the Order of the British Empire, and the following have been created Officers of that Order: Mr. J. D. Brunton, Mr. E. Bury, Dr. F. H. Hatch, Mr. J. C. W. Humfrey, Mr. A. A. Remington, Mr. O. F. A. Sandberg, Mr. J. Kent Smith, Mr. C. E. Stromeyer, and Mr. A. Stubbs. Mr. William Clark was elected Master Cutler of Sheffield, and Dr. Paul Girod has had conferred upon him the Cross of the Chevalier of the Legion d'Honneur.

FINANCE.

The statement of accounts for the year 1920 has been duly audited and vouched for by Messrs. W. B. Keen & Co., auditors of the Institute, and is now presented by the Hon. Treasurer for the approval of the members. The total receipts from all sources, but excluding the income of the Carnegie Scholarship Fund, were £8419. The expenditure for the year was £7622. The balance to the credit of the Institute for the year under review was therefore £797. The income and expenditure for the five previous years are shown below:

			Income.		Expenditure.
1915	.	.	£4816		£4275
1916	.	.	4767	..	4208
1917	.	.	5427	..	5202
1918	.	.	5792	..	6128
1919	.	.	5979	..	7088

It will be seen that both the income and the expenditure exceeded those of any previous year in the history of the Institute. It will be remembered that in 1919, a year in which the expenditure exceeded the income by £1109, a Committee, consisting of Mr. Illtyd Williams (Hon. Treasurer), Mr. Steer, Sir Peter Rylands, and Mr. Harbord,

was appointed to review the whole financial situation. That Committee decided, in the first place, to make a general appeal to the members voluntarily to increase their subscription for the year in question, and secondly to recommend to the members that the subscription in respect of future years should be raised, and that the Bye-laws of the Institute be formally amended to enable that to be done. As the result of the appeal, no less than 876 members responded by voluntary subscriptions amounting in the aggregate to a sum of £1773, and the Council take the present opportunity warmly to thank those members for their generosity. But for the sum received it would again have been necessary to report a deficiency. Notice of a resolution to amend Bye-Laws 21 and 22, relating to annual subscriptions and life compositions, was, in accordance with Bye-Law 10, given at the Autumn Meeting in 1920. It is therefore before the members as a substantive resolution at this meeting, no notice of alteration of the terms of the resolution having been notified at the Autumn Meeting. The effect of this resolution, the text of which will be found in the current Journal and in the present programme, will be to raise the annual subscription of members resident in the United Kingdom and elected at the May Meeting in any year from £2 2s. to £3 3s., and of members resident abroad from £2 2s. to £2 12s. 6d. Members elected in the autumn will pay half the increased rates in respect of the year of their election, and the scale of composition fees has been revised.

As in the last few years, the greater part of the increased expenditure of the Institute has been due to the steadily increasing cost of printing and binding. A saving has been effected in paper by purchasing direct, and the price has fallen slightly, although it is still far higher than it was during the pre-war years. Every endeavour has therefore been made to economise by restricting the length of papers submitted for the Proceedings, and the number of plates, while at the same time every care has been taken to prevent the efficiency of the Proceedings or the work of the Institute suffering in the process. On the other hand, there has been a satisfactory increase in the sales of the Journal, which has partly balanced the increased cost of publication.

MEETINGS.

The Annual Meeting was held on Thursday and Friday, May 6 and 7, 1920, at the Institution of Civil Engineers, by kind permission of the Council of that Institution.

On the evening of Thursday, May 6, the Annual Dinner was held at the Connaught Rooms, the Rt. Hon. Sir Robert Horne, G.B.E., K.C., President of the Board of Trade; the Rt. Hon. John Hodge, M.P.; and Sir J. J. Thomson, O.M., F.R.S., being amongst other distinguished visitors present. After the dinner the members and guests inspected a number of exhibits of metallurgical interest displayed in the Grand Hall and in other rooms reserved for the purpose, including an exhibition and demonstration of X-ray apparatus kindly arranged by the X-Ray Section of the British Electrical and Allied Manufacturers' Association, and by the Research Department of Woolwich Arsenal. A number of kinema films of great interest were also shown in the Grand Hall. Engrossed letters of thanks were sent to all those who had kindly assisted in making the necessary arrangements.

The Autumn Meeting was held at Cardiff, the headquarters of the South Wales Institute of Engineers having kindly been put by the Council of that Institute at the disposal of the members. Over five hundred members and ladies registered their attendance, and lavish hospitality was afforded by the Reception Committee, of which the Rt. Hon. The Earl of Plymouth was Chairman and Mr. Edward Steer, Vice-President of the Iron and Steel Institute, was Deputy-Chairman. The social functions included a reception by the Lord Mayor and Lady Mayoress at the Town Hall, a ball, and a concert, while the members were entertained daily at luncheon by their hosts. Excursions were also arranged to the Vale of Glamorgan and to Chepstow. Visits were paid to the Dowlais Cardiff Works of Messrs. Guest, Keen & Nettlefolds, to the Ebbw Vale Works, and to the works of Messrs. Baldwins, Ltd., at Port Talbot, as well as to the Bute, Barry, and Newport Docks, and to works in Swansea, where on the evening of the last day members were entertained at a banquet given by the Swansea Manufacturers and the Chamber of Commerce and attended by 650 persons. An account of the visit and excursions has been printed in the Journal of the Institute.

The Council take the present opportunity of again thanking their generous hosts, and the Chairman, Deputy-Chairman, members of the Reception Committee, and firms, to whom formal letters under seal of the Institute have been addressed. The Council also wish to record their indebtedness to the Honorary Secretary, Mr. David E. Roberts, for the excellent arrangements made by him and the valuable services rendered on that occasion. Their thanks are also due to Mr. Lewis Jones, who acted as Honorary Secretary to the Swansea Reception Committee. To both these gentlemen the Council have had the

pleasure of expressing the appreciation of the Institute by suitable presentations.

Thirty-three papers were contributed to the Proceedings of the Institute during the year, and have been reprinted, together with the discussions and correspondence upon them, in the Journal. A list of these papers is as follows :

PRESIDENTIAL ADDRESS. By Dr. J. E. STEAD, F.R.S.

ABLETT, C. A. : " Direct Current compared with Three-Phase Current for Driving Steel Works Plant."

ANDREW, Dr. J. H., J. E. RIPPON, C. P. MILLER, and A. WRAGG : " Effect of Initial Temperature upon the Physical Properties of Steel."

BAKER, Dr. T. and T. F. RUSSELL : " Note on ' The Ball Test.' "

BOOTH, A. L. : " Economic Selection of Coal."

CAMPBELL, Prof. E. D., and B. A. SOULE : " Notes as to Rates of Reaction in Certain Steels at 930° C."

CARLISLE, C. G. : " Electric Steels."

CLEMENTS, FRED : " British Blast-Furnace Practice."

DIXON, WALTER : " The Electrification of the Works and Collieries of the Ebbw Vale Steel, Iron, and Coal Co., Ltd."

EDWARDS, Prof. C. A., H. SUTTON, and G. OISHI : " The Properties of Iron-Chromium-Carbon Steels." Part I., " Thermal Analysis." C. A. EDWARDS and A. L. NORBURY : " The Properties of Iron-Chromium-Carbon Steels." Part II., " Effect of Heat Treatment on Electrical Resistivity."

GREAVES, R. H., and J. J. A. JONES : " Temper-brittleness of Nickel-Chromium Steels."

HANSON, D., and Mrs. HILDA E. HANSON : " The Constitution of the Nickel-Iron Alloys."

HESKETT, J. A. : " The Utilisation of Titaniferous Iron Ore in New Zealand."

HOLLINGS, W. W. : " Variations in the Heat supplied to the Blast-Furnace, and their Effect on the Fuel Consumption."

HONDA, Prof. K., and T. MURAKAMI : " Graphitisation in Iron-Carbon Alloys."

HONDA, Prof. K., and T. MURAKAMI : " On the Structural Constitution, Hardening and Tempering of High-Speed Steel containing Chromium and Tungsten."

HONDA, Prof. K., and S. SAITO : " On the Formation of Spheroidal Cementite."

HUGHES, W. E. : " Some Defects in Electro-deposited Iron."

HUTCHINSON, A., and E. BURY : " The Rough Cleaning of Blast-Furnace Gas at Skinningrove by the Lodge Electrostatic Process."

LEWIS, EDWIN H. : " Iron Portland Cement, with a Classification of Cements made from Blast-Furnace Slag."

McWILLIAM, Dr. ANDREW : " Indian Iron Making at Mirjāti, Chota Nagpur."

MONYPENNY, J. H. G. : " The Structure of some Chromium Steels."

NORBURY, A. L. : " The Effect of Various Elements on the Electrical Resistivity of Iron."

PRESTON, G. F. : " Practical Notes on the Design and Treatment of Steel Castings."

RIDSDALE, C. H. : " The Valuation of Ores and Iron-making Material."

ROGERS, Dr. F. : " Brittleness of Nickel-Chromium and other Steels." Part II.

ROSENHAIN, Dr. W., and D. HANSON : " Intercrystalline Fracture in Mild Steel."

SCHNEIDER, EUGÈNE : " An Investigation of Various Forging Operations carried out under Hydraulic Presses."

WHITELEY, J. H. : " Experiments on the Deoxidation of Steel with Hydrogen."

- WHITELEY, J. H.: "The Distribution of Phosphorus in Steel between Points Ac_1 and Ac_3 ."
- WILSON, JNO. F.: "Notes on Slag Conditions in Open-Hearth Basic Steelmaking Practice."
- WRIGHT, H. E.: "Chemical and Thermal Conditions in Blast-Furnace Practice."
- YANESKE, B., and G. A. WOOD: "The Reduction of Silicon from the Slag in the Acid Open-Hearth Process."

BESSEMER MEDAL.

The Bessemer Gold Medal for the year 1919 was awarded to Mr. Harry Brearley, Member of Council, in recognition of his distinguished services in the advancement of the metallurgy of iron and steel.

GOLD MEDAL OF THE BLACKSMITHS' COMPANY.

At the Annual Meeting in 1919 it was announced that the Court of the Worshipful Company of Blacksmiths had decided to award, in consultation with the Council of the Institute, the Freedom of the Company, together with a Gold Medal bearing the Arms of the Company, for presentation annually to a member of the Iron and Steel Institute. The Council recommended that Mr. W. H. Cathcart, the author of a volume entitled "Science in the Smithy," should receive the award for 1920, and this was accordingly conferred upon him at a Court of the Company held in London in May.

ANDREW CARNEGIE RESEARCH FUND AND MEMOIRS.

Nine applications for grants were received during the year, and the following awards have been made:

- Dr. J. NEWTON FRIEND (Worcester), £100 to carry out field tests on the corrodibilities of wrought iron, steel, special steels, cast iron and typical non-ferrous metals.
- R. M. KEENEY (Colorado, U.S.A.), £100 for an investigation on carbon-uranium steels.
- T. F. RUSSELL (Rotherham), £100 for an investigation on the constitution of chromium steels.
- Dr. F. C. THOMPSON (Manchester), £100 to enable him to study surface tension effects in metals, especially ferrous.

Carnegie Scholarship Reports were received during the year from:
 BAINBRIDGE, F.: "The Effect of Fluorspar Additions on the Phosphates in Basic Slag," Parts II. and III.;

ADAM, A. T. : "The Relation of Heat Treatment to Cold-Work in Hypo-Eutectoid and Eutectoid Steels" ;

POLUSHKIN, E. P. : "Alloys of Iron and Uranium" ;
and have been published in Vol. X. of the Carnegie Scholarship Memoirs.

PUBLICATIONS.

The publications of the Institute during the year have consisted of two volumes of the Journal, aggregating 1234 pages and 50 plates, a List of Members, and a volume of Carnegie Scholarship Memoirs, the total amounting to 1555 pages of text and 57 plates, besides numerous illustrations in the text. The Journal contains the usual Reports of the Proceedings and abstracts of foreign technical literature, periodicals, magazines, and transactions relating to iron and steel. The Council have decided that in view of the increased subscription contemplated the custom of binding all members' copies in the familiar cloth cover formerly adopted shall be reverted to.

A decennial index for the period 1910 to 1920 has been prepared in MS. and, together with the index of the technical and scientific literature of iron and steel kept in the Library, is available for members who wish to consult it. In view, however, of the maintenance of the existing high charges for printing and paper its publication has been deferred.

ADDITIONS TO THE LIBRARY.

The additions made to the collection of books include the following donations from authors, publishers, and others, to whom the Council take this opportunity of extending their thanks : "Les Lois de Wöhler," by C. Fremont ; "Le Corroyage de l'Acier," by C. Fremont ; "La Soufflerie," by C. Fremont ; "Gemeinfassliche Darstellung des Eisenhüttenwesens," edited by Verein deutscher Eisenhüttenleute ; "Descriptive Mineralogy," by H. Bauerman ; "History of the Iron, Steel, Tinsplate and other Trades of Wales," by C. Wilkins ; "Detailed Design in Reinforced Concrete," by E. S. Andrews ; "Mathematical Tables," by W. E. Dommett and H. C. Hird ; "Quin's Metal Handbook and Statistics, 1920," by L. H. Quin ; "Foundry Practice," by R. H. Palmer ; "Steelworks Analysis," by J. O. Arnold and F. Ibbotson ; "Wire and Sheet Gauge Tables," by T. Stobbs ; "Weights of Steel Bars, Sections and Plate Tables," by T. Stobbs ; Institution of Civil Engineers : "First Report of Committee on the Deterioration of Structures exposed to the Action of Sea Water" ; "Metallography,

Part I., Principles of Metallography," 1st edition, by S. L. Hoyt ; "Pyrometry," 2nd edition, by C. R. Darling ; "La France au Printemps de 1920," by C. P. E. Schneider ; "Le Voyage des Missions Économiques des pays alliés aux États-Unis et le congrès d'Atlantic City," by C. P. E. Schneider ; "Calcul des Organes des Machines," by J. Boulvin ; Institution of Automobile Engineers : "Report of the Steel Research Committee" ; Comité des Forges de France : "Tableaux Statistiques sur la Production Minière et Siderurgique des Principaux Pays 1864-1913" and "La Siderurgie Française 1864-1914" ; "El problema ferroviario y el de la integral reconstitución económica de España," by J. de Lazurtegui ; "Files and Filing," by C. Fremont, translated by G. Taylor ; "Centenary Volume of Charles Griffin & Co., Ltd."

Amongst the books that have been purchased are : "The Kent Coalfield : its Evolution and Development," by A. E. Ritchie ; "Abrasive and Abrasive Wheels," by F. B. Jacobs ; "Les Contrats de 1907, 1908, et 1913 entré l'État suédois et les sociétés de Luossavaara-Kiirunavaara, Gellivare et Grängesberg-Oxelösund," by P. Nicou ; "Idées générales sur les installations d'aciéries et de gros laminaires," by L. Jacques ; "La Tourbe et son utilisation," by P. de Montgolfier ; "Les Métaux speciaux," by J. Escard ; "Précis de Métallographie Microscopique," by L. Guillet and A. M. Portevin ; "Scrap Metals : Study of Iron and Steel Old Material, its Preparation and Markets," by G. Manlove and C. Vickers ; "Metallurgical Laboratory Notes," by H. M. Howe ; "Steel and its Treatment," by Houghton & Co. ; "Tungsten Ores," by R. H. Rastall and W. H. Wilcockson ; "Die Verwendung der Hochofenschlacke im Baugewerbe," by A. Guttman ; "Die norwegischen Eisenerze," by G. Nicolai ; "Handbuch der Regionalen Geologie," 20 Heft, Band III. Ab. 1. The British Isles ; "Die Südrussische Eisen-industrie," by H. Klein ; "Principles, Operation and Products of the Blast-Furnace," by J. E. Johnson ; "Les Fours electriques industriels," by J. Escard ; "Blast-Furnace Construction," by J. E. Johnson ; "Walzenkalibrierungen," by J. Dehez ; "ABC of Iron and Steel," edited by A. O. Backert ; "Das schmiedbare Eisen," by P. Oberhoffer ; "Die Schneidstähle," by E. Simon ; "Coal," by J. H. Ronaldson ; "Handbuch der Eisen und Stahlgiesserei," vols. i. and ii., edited by C. Geiger.

APPOINTMENT OF REPRESENTATIVES.

The President continues to represent the Institute on the General Committee of the Royal Society for administering Government

Grants for Scientific Investigations. Sir W. H. Ellis, G.B.E., and Professor Henry Louis represent the Institute on the Board of the National Physical Laboratory, and Sir Hugh Bell, Bart., represents the Institute on the Board of Governors of the Imperial College of Science and Technology. The Institute representatives on the Engineering Standards Association are Dr. Cooper, Mr. Mannaberg, and Mr. Talbot. On the Sub-Committee of that Association for the Standardisation of Galvanised Sheets, Mr. C. Dorman continues to serve, while Mr. E. Spencer is the Institute representative on the Sub-Committee for Special Steels for Motor-Car Construction, and Mr. H. J. Yates and Mr. F. W. Harbord, C.B.E., on the Sub-Committee for Cast Iron, working under the direction of the Sectional Aircraft Committee. On the newly formed Sectional Committee for Chemical Engineering the Institute is likewise represented by Mr. Harbord. Lord Invernairn of Strathnairn, Mr. H. Breasley, Mr. J. H. S. Dickenson, Mr. D. Flather, and Dr. W. H. Hatfield represent the Institute on the Committee on Special Steels for Automobile and Aircraft Construction of the Institute of Automobile Engineers. Mr. Harbord is the representative on the British Refractories Research Association, and Dr. Cooper, Mr. Mannaberg, Mr. Hatton, and Mr. Talbot represent the Institute on the Committee on the Improvement and Development of Basic Slag, formed by the Ministry of Agriculture and Fisheries. Professor Turner represents the Institute on the Grey and Malleable Iron Research Committee of the Board of Industrial and Scientific Research. On the Technical Committee of Lloyd's Register of British and Foreign Shipping the Institute is represented by Lord Invernairn and Mr. L. Ennis, and Mr. Dickenson represents the Institute on the Technical Committee of Motor Industries. Sir Robert Hadfield, Bart., F.R.S., and Professor Louis represent the Institute on the Conjoint Board of Scientific Societies, and Sir Robert Hadfield also represents the Institute on the British Association Fuel Economy Committee and on the Court of Sheffield University, while on the Courts of Liverpool University and of Bristol University, the Institute is represented by Sir Peter Rylands and Mr. W. R. Lysaght, C.B.E., respectively. Mr. Harbord is the representative on the Advisory Board of the Royal School of Mines, and on the Federal Council for Pure and Applied Chemistry.

GRANTS TO OTHER ASSOCIATIONS.

During the year the sum of £50 was subscribed to the funds of the Conjoint Board of Scientific Societies for general purposes.

CHANGES ON THE COUNCIL.

Dr. J. E. Stead, F.R.S., Vice-President, who had been unanimously nominated by the Council as President-Elect, succeeded Mr. Eugene Schneider as President of the Institute at the Annual Meeting in May 1920.

The Vice-Presidents and Members of Council who, in accordance with Bye-Law 10 of the Institute, were announced at the Autumn Meeting 1920 as being due to retire in rotation at the Annual Meeting in 1920 were: *Vice-Presidents*—Mr. M. Mannaberg, the Rt. Hon. Lord Airedale of Gledhow, and Mr. Francis Samuelson. *Members of Council*—Sir John S. Randles, M.P., Mr. W. R. Lysaght, C.B.E., Col. Sir W. Charles Wright, K.B.E., Dr. J. O. Arnold, F.R.S., and Mr. F. W. Harbord, C.B.E.

No other members having been nominated up to within one month previous to the present Annual Meeting, the retiring members are presented for re-election.

THE IRON AND STEEL INSTITUTE.
BALANCE SHEET, DECEMBER 31, 1920.

LIABILITIES.		ASSETS.	
To Sundry Creditors:—		By Subscriptions in arrear, since received	
Journal Printing and Publishing	£672 0 7	Interest on Investments, since received	£ 45 3 0
Journal Postage	47 7 5	Journal Sales, since received	215 19 0
Library Books and Binding	5 13 8	Journal binding, since received	12 2 3
Office Rent, &c.	185 15 2	Journal Paper—In Stock	1 2 6
Office Furniture	4 17 8	Investments on account of Life Compositions, at cost, as per Schedule	98 3 0
Stationery, Printing, and Postage	57 10 0	Invested Funds of the Institute, at cost, as per Schedule	2,264 17 4
Subscriptions in advance	...	Telephone Deposit	15,553 11 8
Journal Sales. Amount received in advance	...	Amount due from Special Purposes Fund	1 0 0
Bank Overdraft (less Cash in Hand)	...	Cash on Deposit	268 0 0
Carnegie Scholarship Fund:—	...	Cash at Bank and in Hand:—	700 0 0
Sundry Creditors—	...	Secretary's Balance:—At Bank	...
Printing and Postage of Memoirs	£255 5 5	General Account:—At Bank	£380 17 9
Grants due 1919 and 1920	100 0 0	In Hand...	204 14 10
Amount of Fund	...		2 9 9
Accumulated Surplus Income:—	£21,241 5 6		£568 2 4
As at 1st January 1920	£2,353 17 8	Namely:—	
Add Excess of Income over Expenditure to December 31, 1920	440 5 11	Carnegie Scholarship Fund, in Bank	£1,947 19 3
	2,794 3 7	Institute Account, over-drawn	1,379 16 11
	24,035 9 1		£568 2 4
(Investments as <i>per contra</i> , £22,146 16s.)		Carnegie Scholarship Fund:—	
The Iron and Steel Institute Capital Account:—		Investments at cost, as per Schedule	22,146 16 0
As per last Balance Sheet	£15,894 3 0	Interest on Investments accrued due at 31st December 1920, since received	285 19 3
Add Excess of Income over Expenditure for the year	797 13 11	Cash at Bank	1,947 19 3
	—		24,390 14 6
			£43,550 13 3

ACCOUNT OF INCOME AND EXPENDITURE FOR THE YEAR ENDED DECEMBER 31, 1920.

INCOME.				EXPENDITURE.			
To Entrance Fees	...	...	£ 363 6 0	By Salaries (including Overtime)	...	...	£2714 9 0
" Annual Subscriptions (Members)	...	...	4558 11 0	" Office rent, Cleaning, &c.	...	...	720 18 0
" Do. (Associates)	...	...	46 4 0	" Library Books and Binding	...	...	183 0 0
" Life Compositions	...	...	189 0 0	" Office Furniture	...	...	35 9 5
" Voluntary Donations	...	...	1773 8 9	" Autumn Meeting	...	...	224 1 3
" Journal Sales	...	...	809 9 8	" Annual Meeting	...	...	81 10 8
" Interest on Investments	...	£503 3 7	...	" Deficit on Annual Dinner	...	...	32 1 0
" Income Tax recovered to March 31, 1920	...	237 14 5	740 18 0	" Journal Publishing Expenses:—	...	...	...
" Bessemer Medal Fund:—	...	...	...	Printing, &c.	...	£2343 4 9	...
Interest on Investment	...	£11 4 2	...	Abstracts	...	66 12 4	...
Income Tax recovered to March 31, 1920	...	4 16 2	...	Translations	...	10 2 6	...
	...	...	...	Postage	...	163 10 11	...
Interest on Deposit	...	...	16 0 4	Stationery and Printing (including copies of Papers)	...	...	2583 10 6
" Sundry Receipts	...	...	111 11 5	" Postage and Receipt Stamps	...	...	615 0 0
" Sale of Waste Paper	...	...	9 19 6	" Insurance	...	...	137 3 0
	...	...	1 5 8	" Telephone	...	...	11 17 3
	...	...	...	" Traveling Expenses	...	...	21 10 0
	...	...	...	" Auditor's Fee	...	...	21 6 11
	...	...	...	" Sundry Payments	...	...	21 0 0
	...	...	...	" Bessemer Medal	...	...	85 18 8
	...	...	...	" Compassionate Allowance	...	...	15 10 0
	...	...	...	" Income Tax	...	...	60 0 0
	...	...	...	" Excess of Income over Expenditure carried to Balance Sheet	...	...	57 14 9
	...	...	...		...	...	797 13 11
	...	...	£8419 14 4		...	...	£8419 14 4

THE IRON AND STEEL INSTITUTE.

SPECIAL PURPOSES FUND—BALANCE SHEET, DECEMBER 31, 1920.

LIABILITIES.		ASSETS.	
Capital Account:		£9600 4 per cent. Funding Stock, 1960-90	... .. £7619 3 0
Representing Subscriptions received for 1919,		Cash at Bank:	... .. £ 112 7 3
invested <i>per contra</i> £27616 0 0		Current Account	... .. £ 2107 0 10
Add Subscriptions received during 1920 1835 0 0		Deposit Account	... .. 2219 8 1
Amount due to Iron and Steel Institute	£9451 0 0		
Income and Expenditure Account:	268 0 0		
Excess of Income over Expenditure for the			
year ended 31st December 1920 £276 6 7			
Less Balance at 1st January 1920 156 15 6			
	119 11 1		
	£9838 11 1		£9838 11 1

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1920.

INCOME.		EXPENDITURE.	
To Interest on Funding Stock	£269 2 10	By Grants:	
" Interest on Deposit	... ..	Conjoint Board of Scientific Societies	... .. £ 50 0 0
" Income Tax recovered	... ..	" Excess of Income over Expenditure	... .. 276 6 7
	0 2 11		
	£326 6 7		£326 6 7

INVESTED FUNDS OF THE INSTITUTE.

£3744 North-Eastern Railway 4 per cent. Preference Stock, cost ...	...	...	...	...	...	£4,297 6 7
£788 North-Eastern Railway 4 per cent. Guaranteed Stock, cost ...	...	...	...	...	...	1,008 14 0
£79 4s. 5d. "B" Annuity, Scinde, Puni-jaub, and Delhi Railway, expiring 1958, with a Sinking Fund to replace the amount of Stock, cost ...	...	...	...	...	...	1,999 0 7
£50 1s. 8d. "B" Annuity, Great Indian Peninsula Railway, expiring 1948, with a Sinking Fund to replace the amount of Stock, cost ...	...	...	...	...	...	1,267 6 0
£1500 Buenos Ayres Great Southern Railway 4 per cent. Debenture Stock, cost ...	...	...	...	...	...	1,594 12 9
£1000 Commissioners for the Port of Calcutta 4 per cent. Bonds, 1933, cost ...	...	...	...	...	...	982 10 0
£300 Trustees of the Port of Bombay 4 per cent. Bonds, 1933, cost ...	...	...	...	...	...	809 0 0
£750 Great Central Railway 3½ per cent. Second Debenture Stock, cost ...	...	...	...	...	...	659 12 6
£750 Great Northern Railway (Leeds, Bradford, and Halifax) 6 per cent. Guaranteed Stock, cost ...	...	...	...	...	...	1,140 8 6
£511 South-Eastern Railway 3½ per cent. Perpetual Debenture Stock, cost ...	...	...	...	...	...	449 4 5
£1000 War Loan 5 per cent., 1929-1947, cost ...	...	...	...	...	...	945 16 4
£400 National War Bonds 5 per cent., 1922, cost ...	...	...	...	...	...	400 0 0
						<u>£15,553 11 8</u>

INVESTMENTS ON ACCOUNT OF LIFE COMPOSITIONS.

£1330 North-Eastern Railway Irredeemable 3 per cent. Debenture Stock, cost ...	...	...	...	...	...	£1,254 17 6
£335 London Electric Railway 4 per cent. Perpetual Debenture Stock, cost ...	...	...	...	...	...	304 14 11
£335 Metropolitan District Railway 4 per cent. Prior Lien Debenture Stock, cost ...	...	...	...	...	...	333 11 2
£335 North British Railway 4½ per cent., 1875, Irredeemable Preference Stock, cost ...	...	...	...	...	...	371 13 9
						<u>£2,264 17 4</u>

ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.

£2250 Newcastle-upon-Tyne Electric Supply 4½ per cent. Consolidated First Mortgage Debenture Stock, cost ...	...	...	...	...	...	£2,261 10 0
£2600 Great Central Railway 4½ per cent. Debenture Stock, cost ...	...	...	...	...	...	2,384 5 0
£3000 Great Central Railway 3½ per cent. Second Debenture Stock, cost ...	...	...	...	...	...	2,055 13 6
£5000 Great Northern Railway 3 per cent. Debenture Stock, cost ...	...	...	...	...	...	3,186 16 9
£5000 Great Eastern Railway 4 per cent. Debenture Stock, cost ...	...	...	...	...	...	4,080 16 0
£2000 Caledonian Railway 4 per cent. Debenture Stock, cost ...	...	...	...	...	...	1,693 0 6
£2000 North British Railway 3 per cent. Debenture Stock, cost ...	...	...	...	...	...	1,249 12 6
£2000 Taff Vale Railway 3 per cent. Debenture Stock, cost ...	...	...	...	...	...	1,204 5 3
£2560 4s. India 3 per cent. Stock, cost ...	...	...	...	...	...	1,525 3 3
£2300 India 3½ per cent. Stock, cost ...	...	...	...	...	...	1,600 2 9
£1000 5 per cent. War Stock 1939-47 (Surplus Income Invested), cost ...	...	...	...	...	...	£21,241 5 6
						<u>905 10 6</u>
						<u>£22,146 16 0</u>

(Signed) ILLTYD WILLIAMS,

Hon. Treasurer.

G. O. LLOYD,

Secretary.

I have examined the above Balance Sheets and accompanying Income and Expenditure Accounts with the Books and Vouchers of the Institute, and certify them to be correct. I have also verified the Balances at the Bankers and the Securities for the Invested Funds as shown above.

(Signed) W. B. KEEN,

Chartered Accountant.

23 QUEEN VICTORIA STREET, LONDON, E.C. 4,

6th April 1921.

BESSEMER MEDAL FUND (Trustees: Sir HUGH BELL, Bt., Lord AIREDALE, and FRANCIS SAMUELSON, Esq.).

Iron and Steel Institute.

THE WELDING OF STEEL IN RELATION TO THE OCCURRENCE OF PIPE, BLOW- HOLES, AND SEGREGATES IN INGOTS.

By H. BREARLEY, MEMBER OF COUNCIL (SHEFFIELD).

It is well known that perfectly clean surfaces of malleable metals will stick together under pressure at temperatures much below those commonly used for welding. Platinum is a case in point. As that metal does not readily oxidise, worn vessels can be easily repaired by hammering a piece of hot sheet platinum over the defective part. Hot steel can also be welded together under pressure at low temperatures in an atmosphere of hydrogen or other inert gas. Turnings sometimes stick to the cutting edge of tools which are doing heavy work, and it is on record that a cutting tool has been found welded to a heavy forging which was being machined.

Steel oxidises at comparatively low temperatures. The temper colours visible on bright steel heated up to 200° C. and beyond are forms of iron oxide which, as the temperature is raised, pass gradually into the more or less adherent oxide of measurable thickness which we call scale. The scale thus formed is a brittle substance whether hot or cold; it is not malleable or plastic, and cannot be welded together. At very high temperatures the scale melts and could be expressed in the fluid condition from between two metallic surfaces, but the temperature at which it remains sufficiently fluid is near the melting point of steel. At such high temperatures the fluid oxide scale reacts with the carbon of the plastic steel, liberating carbon monoxide, or dioxide, which forms blisters. It is, therefore, not practicable to make a respectable weld without using some means of lowering the melting temperature of the scale, and also modifying its oxidising effect on the hot steel.

In order to flux the scale which forms on heating iron and steel, the blacksmith uses sand. The sand-scale slag thus formed should be such as is fusible at temperatures some hundreds of

degrees below the melting point of either the scale or the sand. Its fusibility varies with the respective proportions of scale and sand used. Too much of either constituent produces a less fusible flux. Since the amount of one of the constituents—the scale—cannot be determined, the most effective quantity of sand to use can be selected only by skilled judgment ; it depends on the amount of scale needing to be fluxed, and the area to be covered by the fusible sheath which cleans the surfaces and shields them from further oxidation.

Being produced under empirical conditions which are so difficult to control, there is no wonder that welds apparently similar are really of varying quality. The best of them are never perfect, though statements to the contrary are frequently made. A weld may appear under certain test conditions to be stronger than the adjacent part, for two reasons : first, because the adjacent parts have been badly overheated and not hammered ; and, second, because the welded part has been superficially carburised by the coke fire and to a corresponding extent that part has a higher tensile strength. Both these conditions are due to negligence, and hence, judging from the comparative behaviour of welded and adjacent parts under the stress of a tensile test, we arrive at this amazing paradox—the less skilfully the welding is done the better the weld may appear to be.

The tensile test is not a very satisfactory means of recording the weldability of a steel, or the efficiency of a welding process. Although all welds are more or less defective the position of the defect may be unknown, and consequently when a tensile test-piece has been machined it is a question of pure chance whether a particular kind of defect is in the core of the test-piece or on its surface. In the former position the defect may not greatly influence the test figures ; in the latter position the test-piece breaks either before, or soon after, the maximum stress has been reached, and consequently the ductility figures are very poor. In the same way the tests made on gun-tube forgings, taken transversely, give very erratic results, due not to variations in the suitability of the material for its intended purpose, but to the occurrence of slag streaks haphazard, now in a favourable position, now in an unfavourable position in the test-piece.

In 1911 a further means of examining welds was described

by Dr. Stead. He maintained that "the skilful microscopist can, with absolute certainty, determine whether or not surfaces are welded together, a matter of exceeding importance when considering whether cavities in steel ingots can, or cannot, be welded up." It is quite true that certain differences in welds become clear when sections are examined microscopically. The roll-welded plane iron in Fig. 1 is obviously not so good a weld as the hand-welded plane iron in Fig. 2. It is, however, merely a question of degree. The welded surfaces of Fig. 2 can be torn apart as completely as those of Fig. 1, but it would require a greater effort—neither of them are perfect welds. (See Plate I.)

How near to perfection a weld can be made is a question of great importance to steelmakers. Under rolling or forging conditions a steel may be unweldable and yet an ingot may be forged into sound bars. If, however, such an ingot be cracked, as more are than we like to admit, then it is not forgable, but will crumble under the hammer. This explains why of certain alloy steel ingots having the same composition some forge well and others not at all, or very badly.

Ingot are never quite free from shrinkage cavities, contraction cavities, cracks, or blowholes. It has been proposed that ingots should be made with a volume of deep-seated blowholes sufficient to neutralise piping and thus avoid the necessity of scrapping a discard head. As this method of avoiding pipe has been in use for many years it is fair to assume that such ingots produce billets, bars, and sheets, which are commercially satisfactory for certain purposes. Dr. Stead and others conclude from microscopic evidence "that the welding of blowhole cavities as a rule is complete and perfect." Their experimental evidence is obtained by boring a hole into an ingot or billet, fitting a plug of the same material, sealing the joint with a blowpipe, raising to welding heat and hammering or rolling into a bar. If the bar, when nicked and broken across the welded faces, show no signs of the weld, and the microscopic evidence be satisfactory, it is assumed that the weld has been perfectly made.

If by perfection we mean a welded joining which is in all respects as good as any unwelded part of the same bar, then it may be said that the evidence is insufficient to support the conclusion even so far as the limited experimental conditions are

concerned. The conclusions are a still less satisfactory answer to the question whether blowholes in ingots weld up because a drilled hole is smooth and clean, whereas a shrinkage cavity or blowhole may be uneven, lined with segregates, coated with alumina, or otherwise less favourably disposed to weld completely.

During the war great trouble was caused by the occurrence in aero-engine crankshafts of small cracks whose origin was camouflaged by calling them "hair-lines"; just as, ten or twenty years ago, slag streaks were called "sand cracks" and many other names except slag. The so-called hair-lines arose mainly from ingot defects, notably those occurring in and about the axis of the ingot. These axial defects are the remnants of shrinkage taking place in the nearly solidified ingot. The small volume of impure metal last fluid moves downwards as best it may between the loosely adhering free crystals, filling up shrinkage and contraction cavities as long as it is hot enough, or impure enough, to keep fluid. It is finally frozen in positions, lying like an inverted cone about the axis of the ingot. It is called a "V" segregate because it can be detected by a sulphide print, but the harm lies in the small cavities themselves rather than in the sulphide segregate found in, or near, the cavities.

The "V" cavities are greater when an ingot is cast hot than they are when the same kind of ingot is cast cold. The remedy is to cast cold in a mould tapered as much as is practicable. The remedy, however, does not get rid entirely of the cavities, and one must reckon that the remnants of them may appear either as split centres, if the forging be carelessly done, or as small seams or "hair-lines," however skilfully the forging operation may be carried out.

It has been suggested that minute defects inherent in commercially sound ingots, and small blowholes which may occur accidentally, do not weld up in nickel-chromium steels, because steel containing chromium will not weld. And it has been said that if aero-crankshafts, and other important structural components, were made from nickel steels or, better still, from carbon steels, the greater weldability of these steels would remove all difficulties. When this idea is tested under conditions more favourable than those occurring in practice, *i.e.*, by drilling holes along the axis of a bloom, inserting a machined bar of the same material, and after hermetically sealing the ends, rolling the

bloom into a small bar, which is then nicked and broken, we arrive at very curious results. Some steels tested in this way were ordinary mild steels containing 0·15 per cent. and 0·35 per cent. carbon, a 3 per cent. nickel steel, a 5 per cent. nickel case-hardening steel, and a nickel-chromium steel, such as was used for aero-engine crankshafts. On etched transverse sections of the bars the weld lines were either not visible or slight indications only were discovered after much patient searching. When the bars were nicked and broken across the welded surfaces all the steels, judging from the fractures, appeared to have welded perfectly except the 0·15 per cent. carbon steel and the 5 per cent. nickel case-hardening steel. Unless, therefore, we are prepared to believe that tough mild steels weld less perfectly than nickel-chromium steel, we must question the reliability of both these methods of measuring the efficiency of a weld.

On hardening and reheating the entire series of steels so as to put all of them into a tough condition having Izod figures of over 50 ft.-lbs., we find that not one of them withstands the nicked bar test; without exception they pull apart at the welded surfaces (Fig. 3, Plate I.). These results explain clearly why transverse fractures of nickel steels appear to be more reedy than similar fractures made in ordinary carbon steel, *i.e.*, the nickel steel is tougher and therefore pulls open on the faces of welded blowholes, or slag streaks, more than in the less tough carbon steels; the steel itself is not more reedy in the sense that it contains more slag streaks, or less perfectly-welded blowholes.

It is obviously incorrect to say that steel containing chromium cannot be welded under such conditions as apply to the welding of cavities in ingots. If, however, we are seeking some means of expressing the extent to which such steels weld, as compared with ordinary carbon steel, we should endeavour to state comparative results in concrete figures. No attempt appears to have been made to do this. The method to be described is submitted for consideration in the hope that it may be improved, or a better method may be evolved. Some method, at any rate, is desirable if we are to explain the known difficulties in forging special steel and understand the effects of blowholes and segregates on the properties of steels containing them.

The steels to be examined are prepared as $3\frac{1}{2}$ -inch billets.

A hole 1 inch in diameter is drilled down the axis of the billet, and a turned bar is driven into it and fused over at each end. The cored billet is then rolled into a bar $4\frac{1}{2}$ inches by $\frac{1}{2}$ inch. Impact test-pieces cut from the side and centre of this flat bar may be represented diagrammatically as in Fig. A. The test-piece cut from the side will be broken by a force recorded in foot-pounds which represents the effort required to start a crack at the root of the sharp notch and extend the crack across the specimen. The test-piece cut from the centre of the bar is broken in the same way, but it will require a somewhat greater force to

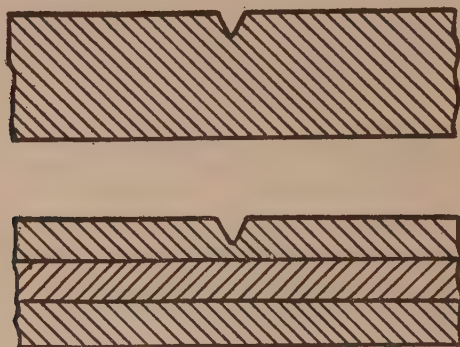


FIG. A.—Impact Test-Pieces cut from Cored Bars.

extend the crack across the specimen, depending on the perfection of the weld between the core and inside of the hollow billet. If no welding has occurred the crack will come to a dead stop when it reaches the core or leaves it, and a new crack would need to be started in each case. This, as we know, absorbs a great deal more energy than is required to propagate a crack which has been already started.

Very hard steels have low impact values because the material in and about the notch is not able to distort, and such steels, even in the form of cored bars, break readily across whether the weld is a good one or not. Conversely, steels having low impact values, whether they are very hard or not, fracture readily across welded cores, and this explains the insufficiency of the nicked bar test as an indication of good or bad welding. To pull a weld

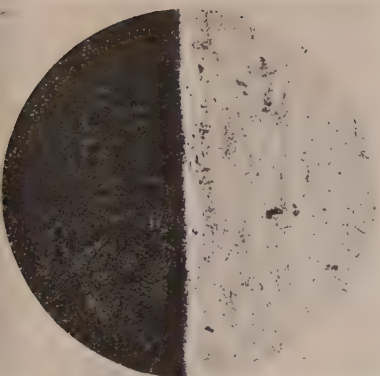


FIG. 1.

Section of Roll-welded Plane Iron.

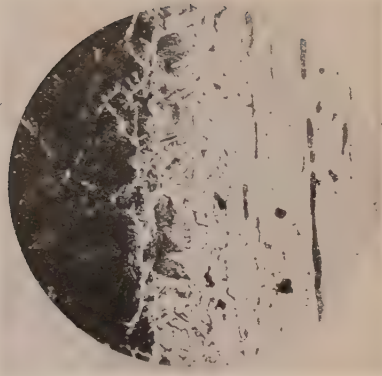


FIG. 2.

Section of Hand-welded Plane Iron.

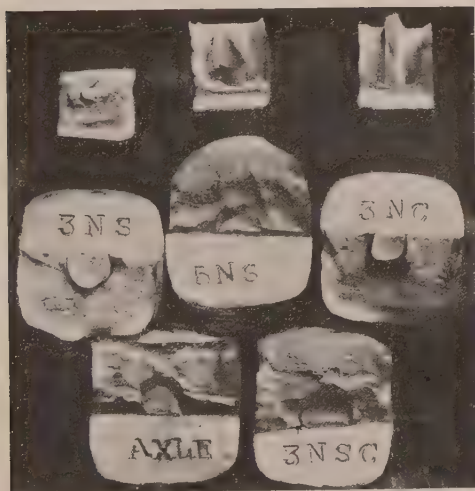


FIG. 3.

Fractures of Toughened Bars showing Cores.

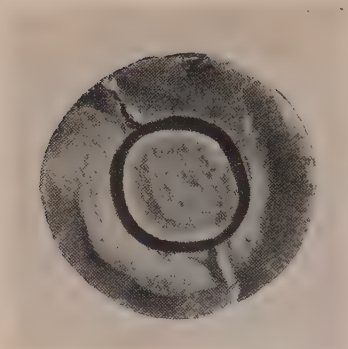


FIG. 4.
Fractured Tensile Piece showing Core.

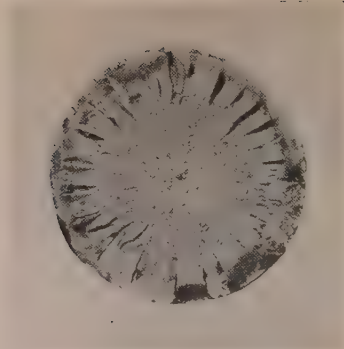


FIG. 5.
Fractured Tensile Piece—no Core Visible.



FIG. 6.
Unetched Micro of 3 per cent. Nickel Steel "B." $\times 50$.



FIG. 7.
Etched Micro of Carbon Steel "A." $\times 250$.

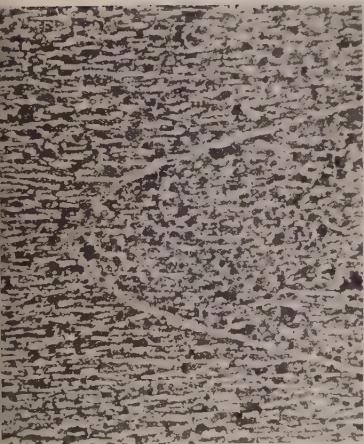


FIG. 8.
Etched Micro of 3 per cent. Nickel
Steel "B." $\times 50$.

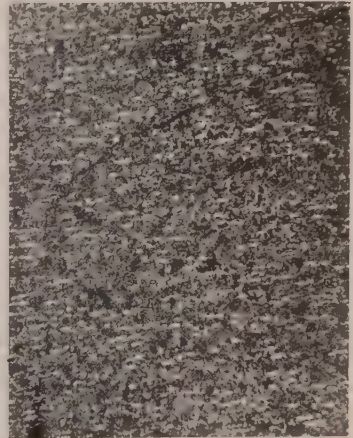


FIG. 9.
Etched Micro of 3 per cent. Nickel-
Chromium Steel "D." $\times 50$.

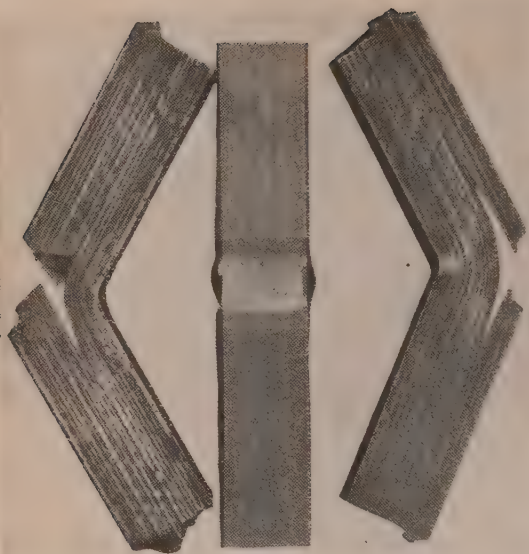


FIG. 10. Broken Impact Pieces from Cored Bars.



FIG. 11. Segregated Boiler Plate.

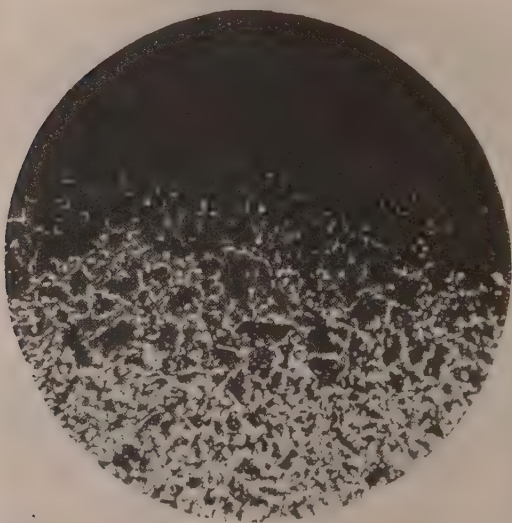


FIG. 12. Photo of Machine Knife. $\times 100$.

apart, if it can be done, the material should be put into a tough condition. The proposal is to measure the perfection of a weld in terms of the degree of toughness which must be induced in the steel before the weld can be pulled apart.

A series of specimens cut respectively from the edge and centre of the flat bar, prepared as described, are hardened and tempered in stages of 100° C. up to say 700° C. These are broken on a standard Izod machine, and the impact value of the edge specimen whose corresponding piece cut from the centre is split along the weld is taken as the welding figure. The following examples will explain the working of the process :

Steel A.

Carbon. 0·34 Silicon. 0·22 Manganese. 0·75 Sulphur. 0·052 Phosphorus. 0·057

Treatment.	Degrees C.	Impact Edge. Ft.-lbs.	Impact Centre. Ft.-lbs.
Oil-hardened at 850° C. and tempered at . . .	none	7	18
" . . .	100	4	5
" . . .	200	9	12
" . . .	300	3	6
" . . .	400	12	20
" . . .	450	28	48
" . . .	500	44	112
" . . .	550	50	120

Steel B.

Carbon. 0·34 Silicon. 0·23 Manganese. 0·71 Nickel. 3·26 Chromium. 0·28

Treatment.	Degrees C.	Impact Edge. Ft.-lbs.	Impact Centre. Ft.-lbs.
Oil-hardened at 830° C. and tempered at . . .	none	3	3
" . . .	100	6	7
" . . .	200	17	16
" . . .	300	4	4
" . . .	400	20	31
" . . .	400	24	32
" . . .	450	23	41
" . . .	450	25	70
" . . .	500	39	120
" . . .	500	39	104

Steel C.

Carbon. Silicon. Manganese. Nickel. Chromium.
 0.32 0.23 0.53 3.11 0.06

Treatment.	Degrees C.	Impact Edge. Ft.-lbs.	Impact Centre. Ft.-lbs.
Oil-hardened at 850° C. and tempered at . . .	none	6	15
” . . .	100	10	10
” . . .	200	18	53
” . . .	300	6	8
” . . .	400	30	118
” . . .	450	31	120

Steel D.

Carbon. Silicon. Manganese. Nickel. Chromium.
 0.35 0.23 0.72 3.57 1.05

Treatment.	Degrees C.	Impact Edge. Ft.-lbs.	Impact Centre. Ft.-lbs.
Oil-hardened at 830° C. and tempered at . . .	none	2	3
” . . .	100	5	27
” . . .	200	15	120
” . . .	300	4	4
” . . .	400	8	19
” . . .	400	6	20
” . . .	450	14	56
” . . .	500	18	120
” . . .	650	52	120

From these results the comparative welding figure selected would be :

Steel “A” = 28 or rather less.
 ” “B” = 20
 ” “C” = 18
 ” “D” = 14 or rather less.

That is to say, these figures represent in Izod foot-pounds the degree of toughness which must be induced in the steels by hardening and tempering in order to pull the welded surfaces apart into a visible gap.

If instead of rolling into flat bars the cored billets are rolled into round, or gothic, or square bars, and tensile pieces are pre-

pared from the bars which have been heat-treated to develop maximum toughness in them, the core will sometimes be visible in the broken tensile test-piece, and sometimes not visible. Of the above series of steels, each of which registered a reduction of area of over 60 per cent., all exhibited a fracture like Fig. 4, except steel "C," whose fracture is represented in Fig. 5. This sample of 3 per cent. nickel steel had, when tested, a maximum stress of 44 tons, an elongation of 29 per cent. on 2 inches by 0.564 inch, and a reduction of area of 65.8 per cent. (Plate II.)

For microscopic observation a transverse section could be cut from the flat bar on which, if the welded faces were well defined, the core would be represented by the outline of an ellipse. The pointed ends of such an elliptical outline could be traced with more or less certainty in all the specimens, but it was more marked in the alloy steels than in the carbon steels. In Fig. 7 the well-marked outline of steel "B" is represented. After etching, the weld in the carbon steel "A" appeared to be outlined by a band of ferrite such as is represented in Plate III., Fig. 7 (magnification, 250 diameters). Nothing similar could be detected in the alloy steels in the rolled or hardened and tempered condition.

In order to increase the separation of ferrite in the carbon steel and promote its separation, if possible, in the alloy steels, samples of each of the four alloy steels were heated to 860° C. and cooled down to 500° C. in nine to ten hours. Etched sections made from these specimens now showed a band of ferrite about the welded surfaces of all the steels except the nickel-chromium steel. Two photomicrographs (Plate III.) are reproduced in Fig. 8 (nickel steel "B") and Fig. 9 (nickel-chrome steel "D").

How far the proposed method of testing welded surfaces, or determining the coefficient of welding, will be found reliable and useful must be shown by further experiment. It is clear, however, that all forms of plastic welding such as are used by the blacksmith, and such as operate in the rolling and forging of piped ingots, produce welded parts unlike other parts of the bar, inasmuch as the welded surfaces can be pulled open, and the free ferrite about them is quite abnormal.

The appearance of free ferrite about welded surfaces recalls the occurrence of the banded ferrite structure in mild steel plates and bars. The banded structure has been ascribed to micro-

segregation of phosphorus. On the other hand it has been suggested that non-metallic impurities in steel in the form of slag streaks, &c., act as nuclei around which the ferrite gathers as it falls out of solution, just as sugar candy crystals form about a thread suspended in the liquor. Whilst the formation of free ferrite on the welded faces falls naturally into its place as a special instance of the effect of nuclei action, it is difficult to see how it can be related to phosphide segregation. Referring to Fig. 9 it may be suggested that the limited amount of free ferrite formed under the conditions of cooling was insufficient to form envelopes about both the slag streaks and the welded faces. At any rate it should not be concluded that nickel-chromium steels behave exceptionally until lower carbon steels of the same type, or more slowly cooled steels in which free ferrite exists abundantly, have been observed.

The conditions, described in the earlier part of the paper, under which the coefficient of weldability is determined, are obviously empirical, and it would probably be necessary to adhere to given dimensions of billet, the inserted core, and the rolled flat bar in order to get consistent results. To observe the effect of deviations a 4-inch square billet was prepared with the usual 1-inch core, with a half-inch core and with a half-inch hole, the end only of which was plugged. In the rolled flat bar the welded surfaces would of course be a single one in the case of the half-inch plugged hole, and double ones in the cases of the half-inch and 1-inch cores. The welded surfaces would also lie variable distances below the bottom of the notch. The actual figures obtained both on softer and harder steels did not show great variations, and they were all in such directions as might be expected. The effect may be summarised by saying that when the hardened and tempered pieces are sufficiently tough to cause the weld to split open the impact value obtained from the welded pieces depends on the thickness of metal behind the split weld which has to be bent by the pendulum hammer. In Fig. 10 (Plate IV.) the right piece represents the half-inch hole specimen and the left piece the 1-inch core specimen. It would clearly require more energy to bend the latter piece than the former after sufficient distortion had occurred to split the welded faces apart. Whilst, therefore, useful information may be obtained whatever size of billet and bar is used, it is advisable to adhere to fixed sizes if

the results are required to be strictly comparative. The author prefers to insert a core into the drilled billet, as then two welded surfaces occur in the impact test-piece.

Although we may be convinced that no pipe or cavity in an ingot can be completely welded, we need be neither elated nor depressed by the fact. It is no part of an observer's business to allow personal prejudices or commercial prospects to colour his views. An investigator's opinions ought not to be malleable under the stress of convenience. Besides nothing is wholly bad, and what may appear as a defect under one set of circumstances becomes an advantage under another. In this respect we may observe that the degree of imperfection of welds is made manifest by a rise in the impact figure. Were no welding to take place the impact test specimen used would bring the testing machine to a dead stop, although the material was not in a very tough condition. If, therefore, the material of a piped ingot, or a blown ingot, be stressed transversely to the direction in which it has been elongated by forging or rolling, such stresses carried to the point of fracturing will have more work to do than under similar circumstances would be required to fracture such material made from a sound ingot. The plate of a laminated spring is one of the best examples of the truth of this deduction, and as a matter of experiment it is found that a cambered spring plate made from the top of a piped ingot cannot be broken by scragging as easily as a similar plate made from the bottom end of the same ingot. In this sense blown ingots, or those rich in non-metallic impurities, make good spring plates, and it is mainly on this account that Bessemer steel is preferred by many spring makers to the more carefully melted and cast open-hearth steel. To some extent the same advantages apply to straight axles, and they are worth consideration even in relation to rolled tyres. It is very remarkable that the fabled virtue of all good wrought iron, viz., its fibre, should be regarded as a defect in steel. It should be valued of course like the grain in wood, according to its direction, in relation to the stresses put upon it.

That pipe, or blowholes, or any other form of cavity in ingots is apt to be, and usually is, associated with segregated carbon, phosphorus, and sulphur, requires no special proof. If, therefore, the discussion be confined to the welding of ingot cavities it would be instructive to know how far the cohesion of the welded

surfaces is influenced by carbon, phosphorus, and sulphur respectively, and whether the influence of these elements present in the same specimen is additive or otherwise. A few statements on this subject have been made, but they must be regarded as opinions rather than as evidence. It has been said that "the welding up of blowhole cavities in ordinary practice is, as a rule, complete and perfect," and also that "phosphorus concentration in blowholes facilitates welding, and iron relatively high in phosphorus is more readily welded than very pure material." We must remember, however, that this conclusion depends either on microscopic observation which may be illusory, or on the nicking and breaking method which may be misleading. Of the two methods of judging a weld it is claimed that "nicking and breaking was a more certain method than that of the microscope." As the nicking and breaking method carried out on bars in the forged and rolled condition would lead us to believe that all hardening elements added to steel, including phosphorus, improve its welding properties, its results obviously need to be interpreted with caution.

It is generally stated, without any experimental warrant being adduced, that all segregates existing in ingot cavities decrease the weldability. It has been assumed that in the absence of segregates a perfect weld could be made, and as segregates and imperfect welds are often found together the presence of the segregate and the degree of imperfection are regarded as cause and effect. This conclusion is untenable now we know that perfect welds cannot be made even under the most favoured conditions.

In 1912 Dr. Stead prepared two crucible ingots containing 0.020 per cent. sulphur. One was blown and the other sound. Both were forged into round bars and parts of each bar were turned into annular rings. When drifts were forced into the rings those made from the blown steel broke with 50 per cent. less extension than those made from sound steel. A sulphur print taken from the forged bars showed clearly the location of the blowholes, because segregates had been pressed into them by such forces as operate in every solidifying ingot. The weakness of the one set of rings as compared with the other was ascribed to the presence of sulphide segregates. Such a conclusion, how-

ever, is only justified if it can be shown that identical rings made from blown steel containing no segregated sulphide are practically as strong as rings made from sound steel. A direct experiment on these exact lines cannot be made because it is impossible to produce commercial ingots containing blowholes without these holes being more or less lined with segregates. But as the blowholes could not weld completely under any circumstances it is likely that the rings were weaker in one case than the other, quite apart from any question of segregation.

To test this supposition a dozen small holes were drilled lengthwise to a depth of 8 inches into a 4-inch billet. Each hole was cleaned, dried, and filled with petrol vapour before being closed by plugs 1 inch long driven in with a sledge-hammer, and fused over with the oxyacetylene blowpipe. The billet was rolled into a $\frac{7}{8}$ -inch round bar. From the sound and unsound parts of the round bars annular rings were turned. The rings were drifted, as in Dr. Stead's experiment, until they broke, with the following results :

Steel A. 865.

Carbon.	Silicon.	Manganese.	Sulphur.	Phosphorus.
0.46	0.15	0.70	0.040	0.030

Condition of Steel.	Percentage Increase in Diameter of Drifted Rings made from	
	"Unsound" Part.	"Sound" Part.
As rolled	2.4	14.5
"	3.4	12.6

Steel Y. 339.

Carbon.	Silicon.	Manganese.	Sulphur.	Phosphorus.
0.15	0.23	0.92	0.060	0.018

Condition of Steel.	Percentage Increase in Diameter of Drifted Rings made from	
	"Unsound" Part.	"Sound" Part.
As rolled	2.7	20.8
"	7.8	22.9

Sulphur prints were made from both the sound and unsound bars, but there was no distinction between them. These results appear to negative the conclusion that the annular rings in Dr. Stead's experiment broke prematurely on account of sulphide segregation; they would have broken prematurely in any case, because blowholes or any other cavity in an ingot do not weld completely however much work may be put on to the material during forging or rolling.

The difference in behaviour between the sound and unsound rings when drifted is a striking example of the disadvantages of blown or piped steel when stressed transversely. Gun tubes or gas cylinders are stressed more or less like the drifted rings, though they are, of course, not made into hollow tubes in the same way, and a welded blowhole would lie more favourably in either case than in the drifted rings. Gun tubes are not made from blown ingots, but blown ingots of mild steel are consciously made into billets and blooms for tubes and gas cylinders. Whatever commercial warrant there may be for this practice it would appear to be undesirable metallurgically, because blowholes induce spot segregates, and are undesirable mechanically because the incompletely welded cavity decreases the resistance of the steel to the working stresses.

There seems to be little doubt that sulphur has been blamed for defects due to other causes, and one wonders whether this segregate in particular is quite as harmful as it is made out to be. Take, for example, a piece of boiler plate which has laminated on flanging. The metallurgist applies a piece of acidified photo paper and produces a sulphur print (Fig. 11), showing that the defective part corresponds with a segregated area. According to text-books segregates are known to be harmful and high sulphur is reputed to cause red-shortness. The inference is easy, but the obvious explanation is, in many cases, not the correct one. It is true that sulphur compounds segregate in steel; so do phosphorus, and so also do carbon compounds. Of these the one most easily detectable, and almost invariably detected, by the method of sulphur printing is sulphur, but it is not therefore necessarily more culpable than either phosphorus or carbon. Further, in perfectly sound ingots (except perhaps very large ones) mass segregation is not possible. In such ingots as are practi-

cally sound, that is to say, in the best type of commercial ingots, mass segregates are found only where there are, or have been, cavities. The pipe in a piped ingot is lined with segregates and most cavities in a blown ingot are distinguishable in the forged blooms by the segregates which filled, or partly filled, the cavities in the ingot stage.

On reconsideration of the laminated boiler plate we must regard the dark centre part on the sulphur print first as evidence that the ingot material from which the defective article was made was piped. The sulphide segregates enable us to draw this important conclusion, but whether the segregates as a whole have aggravated the defect depends on whether or not they have interfered with the chances of the pipe welding up. The facts are broadly the same with respect to spot segregates. In either case, that is to say, in relation to both axial segregates and spot segregates, the real cause of the trouble is either a pipe or a blow-hole, and it is not reasonable to blame the segregate, which in the nature of things gets squeezed into these cavities, unless they interfere with welding. A series of five crucible steel ingots containing from 0.06 per cent. to 0.17 per cent. sulphur, but otherwise similar in composition, have been prepared in order to observe the influence of sulphur on the welding figure. The results are not ready for publication, but so far as they go they show that either in the rolled condition or in the hardened and tempered condition the high sulphur steels weld as well as, and on the whole rather better than, the low sulphur steels. This, and general experience, lead the author to assume that of the segregates themselves, the least harmful, taking all things into account, is probably sulphur. By pure chance it happens to be easily detectable, and it is thus forced to turn king's evidence against its associates.

It would be something of a paradox if, presuming it could be entirely eliminated, sulphur were after all retained in, or purposely added to, steel in order to serve as witness. A sulphur print of an ingot section is one of the best records of the conditions under which an ingot is formed. It may indicate the casting temperature; whether top or bottom casting methods have been used; whether blowholes later filled up have existed earlier in the partly fluid ingot; and many other useful things to the

observant investigator. It is by far the most valuable means available for determining whether a forging became axially unsound on hammering or was made from piped material. It indicates at once the presence of spot segregates in forged or machined articles, and either facilitates the machining or suggests that the material should be scrapped, and finally it is an indispensable touchstone for the careful steelmaker who is making steel for such special purposes as rifle barrels. In nearly every case a sulphur print is less valuable as an indication of sulphur than of more harmful things of which its presence gives warning. A sulphur print is worth many sulphur determinations, and we could hardly spare the tell-tale sulphur altogether—we might then have to add sulphur to our steel, as we know nothing so voluble, so reliable, and so harmless which would serve the purpose equally well.

Very few experienced observers will doubt the possibility of pulling apart welded faces in objects made from blown ingots. The author believes that it can be done, always providing the steel in which they occur is tough or can be made tough by heat treatment. Iron and steel lumps from which bars for machine knives are made are produced by casting very mild steel against the face of very hot tool steel. In the forged or rolled bar the interpenetration is considerable (see Fig. 12). The two materials, however, can be pulled apart along the original faces. Three-ply steel, such as is used for making plough mould boards, is probably produced in a similar way, but the rolled sheet can be split and the iron core separated if the sheet be first toughened by hardening and tempering.

If a billet be drawn down at one end into a bar the unforged part of the billet may be worked up and down in fluid steel as it rises in an ingot mould, so as to heat the billet and drive off adherent gases. Such a billet may then be left in the upper part of the ingot in a highly preheated and clean condition. After forging that part of the ingot containing the billet may be rolled into flat bars and such bars may be tested. After this procedure a core corresponding with the original billet section may always be separated.

From these considerations one would expect that impact test-pieces cut from the centre and from the edge of a flat bar rolled

from an ordinary ingot would frequently give different results. Such differences actually exist, and moreover the difference is most marked when the bar is taken from that part of the ingot which is unavoidably least sound. An ingot cast wide end up and provided with an efficient feeder head is—omitting the feeder head—most nearly perfect in its bottom third and top fourth ; it is less perfect in the centre of its middle half. These facts are clearly discernible in a sulphur print made from a sound ingot which has been sectioned longitudinally through its centre. Quite in accordance with the sulphur print indications one finds that variations in impact test-pieces cut from the edge and centre of flat bars are greater or less, according as the bars have been made from the middle or one or other extremity of the ingot.

DISCUSSION.

Dr. J. O. ARNOLD, F.R.S., Member of Council, said the author referred broadly to segregates, and pointed out, very properly, that they might consist of carbon, phosphorus, and sulphur. In what form, however, did they exist? He thought the conclusion must be arrived at that arguments which would apply to a segregate of one of these elements would not apply to the others. It was not disputed that an ordinary steel with, say, 0.5 per cent. of carbon and 0.5 per cent. of manganese, contained a double carbide of iron and manganese. Phosphorus always existed as Fe_3P in solid solution, and in all ordinary steels sulphur undoubtedly existed for practical purposes as MnS (manganese sulphide). Manganese sulphide (MnS) was not likely to weld with steel. It was as plastic as iron itself, but the MnS always occurred in layers in the steel, and where it occurred no very serious breaking was noticed. Did the layers act in the ordinary way as a mechanical mixture where there was a fracture across every flake of manganese sulphide? The flakes of MnS could be recognised regularly with the microscope, and yet were very firmly attached to the iron or mild steel surrounding them. What was holding them? He submitted it was necessary to explain more carefully the behaviour of those fundamental segregates, and how they were acting in the mass, and in that connection he thought it was necessary to take into consideration the question of surface tension, so ably developed by his colleague, Dr. Thompson.

Mr. H. DODO (London) said one of the reasons given in the paper why a weld might appear under certain test conditions to be stronger than the adjacent part was that the welded part had been superficially carburised by the coke fire, and to a corresponding extent had a higher tensile strength. It would, however, be much more reasonable to use the term "yielding strength" instead of "tensile strength," because the effect of the super-carburisation in the welded part would be to give rather a higher yielding strength as compared with the adjacent part. In the case of an ordinary tensile test and stress strain diagram, the adjacent part would reach yielding point before the welded part did. The adjacent part would therefore be elongated on applying stress, and consequently reduction would occur and the piece would break at that point.

Dr. WALTER ROSENHAIN, F.R.S. (National Physical Laboratory), said the idea that a weld could ever be perfect was probably quite as illusory as the paper led members to believe; in fact, the degree of

imperfection in welds other than internal ones was generally very great. The difficulty was that it was never known whether a weld was only slightly imperfect or very bad indeed. With regard to internal welds, he had recently had an opportunity of examining some cavities in steel, and although they looked perfectly bright there could be no question about it that they were not clean metal surfaces. With regard to the other question, whether a segregate, that was, a non-metallic material lying on the surface of the steel, hindered or did not hinder welding, he thought it could hardly be disputed that if it were impossible to press the metal to the metal it would be impossible to obtain a weld. That was known perfectly well from the blacksmith's experience. A blacksmith put a fusible slag on the surface of the welding metal and squeezed it out. In the interior of a blowhole there was no possibility of squeezing anything out, and consequently there must be a mechanical difficulty in getting a perfect weld under such conditions. What was commonly called a slag enclosure might be obtained, a non-metallic enclosure remaining behind, but that could hardly be regarded as assisting to close up blowholes. The only sound steel was sound steel. He thought Mr. Brearley had made a great advance in the method of testing the perfection or otherwise of welds, but before feeling quite satisfied with the figures quoted in the paper he would like to recall the fact, of which Mr. Brearley was no doubt already aware, that Izod impact figures were very variable, even in perfectly good material free from all welds and similar defects. Mr. Brearley had based his estimation of the weldability of a steel on certain Izod impact figures, and quoted apparently single figures. He (Dr. Rosenhain) would warn anyone reading the paper and trying to employ the method suggested against being content with anything less than a large number of Izod figures upon which to base such a comparison, otherwise misleading views as to the relative weldability of two kinds of steel might be obtained. Finally, he desired to say that he did not think quite such a debt of gratitude was owing to sulphur in steel as Mr. Brearley would have the members believe. It was a very heroic, not to say humorous, thing to stand up as the champion of sulphur, but he would remind Mr. Brearley that it was possible to find out quite a lot about the past history of steel from its macrostructure obtained by etching with any of the cupric reagents or certain other well-known means, and even if there were no sulphur and the phosphorus were very low, it was still possible to obtain all the information desired, although not perhaps quite so easily as from a sulphur print. He thought any metallurgist who read the sulphur print as indicating merely the distribution of sulphur and nothing else was neglecting nine-tenths of the valuable information it conveyed. It could be regarded as a guide to the various substances present in the steel associated with sulphur, although not necessarily as cause and effect. The paper put the whole question of the character of welds on a sounder basis

than before, although the welds themselves were apparently not as sound as earlier workers believed.

Dr. L. AITCHISON (Birmingham) said it would be of great interest if Mr. Brearley could give a reasonable method of determining whether the unsoundness of nickel-chromium steels was more harmful than the corresponding unsoundness of carbon steels. He had therefore turned to the figures given in the paper with considerable interest, because he wanted to possess that particular information which Mr. Brearley rather suggested he could give. He felt, however, some disappointment when he looked at the figures for steels "A," "B," "C," and "D," given on p. 34. Even allowing for the fact, as Dr. Rosenhain had suggested, that they were based on a number of observations, he did not think they led to a very sound conclusion, or that a plain carbon steel welded up twice as well as a nickel-chromium steel. The figures upon which the weldability of the material was judged were ordinary Izod impact test results. Izod impact values did not represent an absolute physical quantity and were only very relative. When impact test results were evaluated they had to be taken in conjunction with the tensile strength of the steel upon which the test was obtained. Mr. Brearley had not quoted the tensile test results, but he (Dr. Aitchison) estimated from the composition of the steels, the size of the bar, and the heat treatment that steels "A," "B," "C," and "D" at the critical welding figures had tensile strengths of 45 tons, 75 tons, 85 tons, and 90 tons respectively. The tensile strength and the impact figures therefore ran together and gave exactly what would be expected if each steel were truly equally tough. The real evidence of the welding figures was that all the steels welded to the same degree, and that steel "A" did not weld twice as well as steel "D." Impact figures could only be interpreted in relation to tensile strength; in his opinion the impact figures and tensile strength went together and showed absolute similarity. Mr. Brearley's method of dealing with the influence of sulphur was very interesting. He had suggested in the paper a method of finding out whether the actual proportion of sulphur in a material had any effect upon the way in which the segregated areas would become what was called sound. It was understood that sulphur would segregate in all ingots, and there was likely to be a higher proportion of sulphur in some form or other in the centre than along the edge. If a series of ingots containing different proportions of sulphur were made and rolled down there would be in each case a different proportion of sulphur in the middle and the outside, and it was possible to test by Mr. Brearley's method whether a high sulphur steel gave a worse ratio between the centre and the outside than a low sulphur steel. He (Dr. Aitchison) had obtained some test results on a series of ingots containing sulphur in the following amounts: 0.062, 0.09, 0.1, 0.13, and 0.17, which showed that the variation in the percentage of sulphur did not in any way influence the ratio between the impact value on

the outside and the centre. Therefore, if Mr. Brearley's method indicated the weldability of the material, it could also be shown, by the experiment he (Dr. Aitchison) had recorded, that the actual quantity of sulphur had no effect upon the way in which the material would weld up. Even a small proportion of sulphur was just as harmful or as harmless as a large proportion.

Analysis of Samples.

	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.
Carbon . . .	0·42	0·41	0·39	0·40	0·42
Silicon . . .	0·16	0·14	0·14	0·14	0·19
Manganese . . .	0·91	0·99	0·95	0·92	1·11
Sulphur . . .	0·167	0·128	0·106	0·090	0·062
Phosphorus . . .	0·028	0·027	0·027	0·027	0·038

<i>Steel No. 2. Oil-hardened from 820° C.</i>			<i>Steel No. 3. Oil-hardened from 820° C.</i>		
Tempering Temperature. Degrees C.	Impact Value, Ft.-Lb.		Tempering Temperature. Degrees C.	Impact Value, Ft.-Lb.	
	Edge Specimen.	Centre Specimen.		Edge Specimen.	Centre Specimen.
400	18	33	400	18	25
450	22	36	450	18	24
500	22	35	500	22	35
550	28	36	550	20	40
600	33	37	600	25	41
650	36	44	650	27	60
<i>Steel No. 4. Oil-hardened from 820° C.</i>			<i>Steel No. 5. Oil-hardened from 820° C.</i>		
500	26	40	500	25	42
550	26	53	550	29	50
600	38	50	600	46	55
650	37	53	650	52	78

Steel No. 6. Oil-hardened from 820° C.

Tempering Temperature. Degrees C.	Impact Value, Ft.-Lb.	
	Edge Specimen.	Centre Specimen.
500	20	43
550	24	42
600	37	61
650	43	61

Mr. J. H. WHITELEY (Saltburn) said the author was hardly justified in drawing the conclusions he had done in regard to the non-weldability of blowholes in steel from the experiments he had made, because in all the experiments carried out the welds had been made in air, and air was certainly not present in steel blowholes. It was well known that when cold ingots were cut the blowholes within were nearly always bright and untarnished, and although they might sometimes contain sulphides and silicates, no oxide was present. Further, he thought it might safely be assumed that, no matter how the equilibrium composition of the gases shifted with increasing temperature, in the presence of carbon in the steel and hydrogen in the blowholes, the character of the gases present would always remain reducing as regards the formation of oxide of iron. Therefore when the two clean surfaces met during rolling or forging they should weld perfectly, because there was nothing to hinder it. He supported that statement by describing some experiments he had made in which he had welded small piles of pure electrolytic iron in dry hydrogen and also in air. On sectioning the welds and etching and examining them under the microscope, he could find no traces of the junctions in the hydrogen experiment, but when air was present the junctions of the welds were plainly visible. Moreover, on applying a severe crushing test to the samples the hydrogen weld stood it perfectly: no cracks nor any indication of weakness at the junctions appeared. In the case of the air welds, however, the steel tended to split apart along the weld junctions, as was the case in the author's experiments. He gathered from Mr. Brearley's reply to the discussion on a similar paper which had been read at Middlesbrough that he was not satisfied with the tests which he (Mr. Whiteley) had made, and he therefore determined to repeat the experiment, and apply the author's own test to the welds. For that purpose he obtained a 1-inch round bar of mild steel containing 0.24 per cent. of carbon and the usual amounts of the other constituents, and bored it at one end to form a tube, closed at the other end. He then inserted a cylinder of the same steel about 2 inches long at the closed end of the tube, the cylinder being split in two longitudinally, so that there would be three welds altogether. He then welded together the end of the tube and the split cylinder in dry hydrogen and forged the welded piece down to a bar $\frac{1}{2}$ inch square. He next made another similar weld in air by inserting a split cylinder in a tube of the same steel about 4 inches long. Here the end of the tube was closed by forcing a small plug of the steel into it. He did not fuse the end over as the author had done; he simply plugged it up, so that the gases would have a chance of escaping during the welding. The piece was then forged down to a bar $\frac{1}{2}$ inch square. For purposes of comparison, he also forged a piece of the original steel down to the same dimensions, so that he thus had three pieces altogether—one welded in hydrogen, one welded in air, and the original piece. He then quenched them in oil, as the author had done, from 900° C.,

and tempered them at 570° C., and impact tests were very kindly made for him by Mr. D. Sillars, Chief Chemist of Messrs. Bolckow, Vaughan & Co. The results of the impact tests, two in each case, were as follows: the original unwelded bar gave 97 and 95 foot-lbs., the bar welded in hydrogen 107 and 103 foot-lbs., and the air-welded gave 110 and 113 foot-lbs. There was no difference in the fractures between the hydrogen-welded and the unwelded bar. The welds made in hydrogen did not strip, but in the case of the air weld traces of the weld junctions could be seen in the fractures, although not quite so pronounced as the author had shown. Under the microscope he could find no indication of the welds, when hydrogen had been used, by any method of etching, but when air had been present the weld junctions could be seen in places. He therefore still held to the opinion that, under right conditions, steel could be welded perfectly, *i.e.* two pieces could be united so that the sample produced might have been forged from a single cast piece. There was one condition in his experiment, however, which did not obtain in the welding of a blowhole. During the welding in hydrogen the gas could escape up the tube from between the surfaces. But in welding a blowhole, if the hydrogen and other gases present were going to escape as the steel was rolled or forged they could only escape by diffusion through the surrounding walls of the steel. If they could not get away entirely in this manner, for one reason or another, then they would have to remain where they were, with the result that a film of gas or series of minute cavities would be present in the finished material; a discontinuity would be present and the steel would not be sound. That, he thought, was the condition which the author had brought about in his experiments, because after inserting the plug he fused over the ends of the cylinders and thus hermetically sealed up the gases. He would therefore suggest that if the author examined his welds very carefully under a high magnification he would very probably find evidence of this sponginess, which would at once account for the marked stripping he had obtained in his tests.

Dr. W. H. HATFIELD (Sheffield) said that with regard to the welding up of cavities and blowholes, there could be no question that the evidence Mr. Brearley had adduced finally and firmly established the fact that if cavities or blowholes were present it was unreasonable to expect that their effect could be entirely removed. That brought him (Dr. Hatfield) to the very important point that in manufacturing steel ingots every care should be taken to ensure that they were free from such internal defects, and the more so in the case of alloy steels and steels to be used for parts which were to be highly stressed. His firms had practically completely adopted an ingot with the broader end at the top and a good refractory head. That meant that the pipe was in the top of the ingot, with perhaps just a little segregate below the pipe, but apart from that all the ingots, also being made

from piping steel, were substantially free from internal defects. As regards ordinary cheap structural steels it was not considered necessary, owing he presumed largely to the cost of production, to scrap from 35 per cent. to 40 per cent. of such top ends of the ingots. Ingots were still being produced without feeder heads and with the narrow end at the top, containing a large number of blowholes. As long as the fact was recognised that ingots which contained blowholes and cavities did, after rolling or forging, contain a weakness where those blowholes or pipes occurred, that was presumably sufficient for the purpose.

He could not agree with Mr. Brearley that sulphur might be carried as high as was suggested. Manganese sulphide was a very brittle, non-metallic substance, and the less there was of it in steel the better. It was quite clear that as far as commercial considerations would permit the amount of sulphur and phosphorus present should be as reasonably low as possible, and he therefore deprecated the suggestion that for spring and similar steels ingots might be used which were high in impurities.

Sir WILLIAM ELLIS, G.B.E., D.Eng., Vice-President, said a discussion on the paper would hardly be complete without going back to a subject which at one time interested the Institute very much, namely, that of fluid compressed ingots. Those ingots were extensively used for big work, and so far as he knew their use was continued. Some years ago, when he was using a large number of those ingots, he found, on cutting them up, that uniform and definite conditions existed in the head, and he made certain experiments on welding which appeared to him conclusive on one point, namely, that even with the existence of a cavity in the ingot head to which oxygen had access, perfect welding, as far as that expression could be used, was possible.

Taking the ordinary case of a compressed ingot where the pressure was applied on the end of the ingot, a thickness on the top and round the outside of 6 inches to 8 inches of solid metal was formed and a pear-shaped cavity was formed, the bottom point of which was about 33 per cent. of the length of the ingot from the top. At that point occurred the area of greatest segregation. He forged the top ends of such ingots down, and when cold cut them up into sections and failed to find any evidence of a cavity having previously existed. From those experiments he held the view that sound welding of such steel in the absence of oxygen was an accomplished fact.

Dr. A. McWILLIAM (Sheffield) said it was curious that the very ancient process with which the paper dealt should still require elucidation, but it was certainly not yet thoroughly understood. Mr. Brearley's study of the subject was a very valuable one. For many years he (Dr. McWilliam) had been much interested in the question of the welding of blowholes, and recently when dealing with the manufacture

of large quantities of certain steels in a works that was not so designed that a method of getting absolutely solid steels could reasonably be used, he decided that he ought to leave a few blowholes in the ingots, sufficient to prevent the formation of pipes, and that those blowholes should be well under the surfaces of the ingots. He did that because the examination of a considerable number of specimens that had failed revealed the pipe as the worst of defects. The success of the process lay in controlling the number of blowholes that would be produced. Under the conditions of labour and management some method had to be arranged so that the blowholes were just sufficient to avoid piping, and not sufficient to make disturbances violent enough to cause a proportion of the blowhole cavities to be connected with the air through the surface of the ingot. If an ingot were made with the right number of blowholes in it there would be a reducing atmosphere within the small cavities, whereas with what was sometimes called a cauliflower top, many of the cavities would come into contact with the outside sufficiently to draw oxygen from the air and become oxidised. Such cavities appeared afterwards in various articles in the form of rokes. Manufacturers had been criticised recently for discussing such questions, which had the effect of disturbing their customers, but it was the due consideration of all such points that was in part at least responsible for the fact that in the vast majority of cases the steel served its purpose well. One of the things for which he had to be responsible in connection with the method of selection of the type of ingot to be made was not to pass judgment from a microscopic examination only, but to see that the material stood an exceedingly severe shock test of the older type. The materials were tried first of all in sample heats, and put through tests very much more severe than those that they were required to stand under the specification, and they stood the test successfully. Although he did not know what happened to the gas, he used to teach that it was highly probable that it would be reabsorbed during the working of the steel, a statement with which he thought Dr. Arnold would agree. In the old days at Sheffield University sulphide constituents were examined in large numbers and with great care, but he did not remember seeing the sponginess to which reference had been made.

Colonel D. CARNEGIE (London) said the paper had brought to his memory a very serious time of trouble in connection with ingots made for shells during the war, largely due to manufacturers not being at the time conversant with the best form of ingot to use for punching shells into shape. He was referring to the experience of Canadian manufacturers in connection with ingots which, when fractured longitudinally, showed spongy places, not ordinary blowholes, in that part of the ingot from which the stipulated "head" had been removed. They were really more contraction troubles than blowhole troubles. In order to save good steel from being rejected several experiments

were made, of which it might be of some interest to relate particulars. Those concerned were convinced that the contraction areas could be welded in the process of forging.

What he was referring to could not be called piped ingots but ingots with contraction cavities having the appearance of a spongy segregate, although not segregated in the ordinary way. The experiments consisted of drilling to different depths shell ingots of the ordinary size used for making a single shell each. After being drilled they were punched in the ordinary way, and usually a button of scale and sometimes of steel was found at the bottom of the cavity, showing that the metal as it gathered around the drilled hole did not weld up where the scale separated the metallic bodies. It was supposed that as the ingots were heated in the furnace, some oxidation in the holes prevented a proper weld. When, however, the same kind of ingots were drilled and plugged, no trace of the plugging was found after being forged. It appeared, therefore, that a suitable weld had been made. Further, when cross-sectional test-pieces were taken from the bottom of the punched ingot the same physical properties were found in the material as in test-pieces taken from the walls of the shell forging. He would like to know how far it was possible to discriminate between the use of ingots for such purposes in which pipes might exist, and where the contents of the blowholes were likely to interfere with the welding, and of ingots not having blowholes coated with oxides, but with clean contraction cavities which, when forged, appeared to weld properly.

Mr. COSMO JOHNS (Sheffield) said steels which contained cavities formed from different gases might be divided into three classes—the first being dead mild steels, used for sheet and plate bars; and the second, steels in which blowholes were always left which welded or closed up. Except in special cases where blisters occurred due to improper casting or melting, such a steel was, from the practical standpoint, good. It was entirely different in composition from the steels in the other two classes. In high tensile carbon steel it had been found from experience undesirable to have blowholes; there must be a sound ingot, and if it were not possible to cast the ingots in the best possible form when making high tensile steels, only the lower or sounder portion of the ingots should be used, and the other portion employed for something less important. The third class consisted of alloy steels—special steels which were treated differently and used for different purposes. They were stressed transversely, and it was the transverse tests that had to be provided for, being the only ones used. No general statement as to the reliability of welds could apply to all steels. As a matter of fact, the so-called perfect ingot of the inverted shape was used to his knowledge at Landore in making dead mild tinplate steels, and it was used throughout South Wales for making mild steels. Theoretically, if two chemically clean surfaces of iron

were pressed together at high temperature in the presence of hydrogen or in an absolute vacuum, the two surfaces could be welded no matter what the steel was. In practice, however, this could never be done. It was possible to get near enough to it in the case of mild steel, because there was not high silicon in the steel nor the same class of non-metallic impurities; but theoretically it was possible to weld up any two clean surfaces, provided oxygen was kept away. The difficulty in practice was that with hidden cavities it could never be ascertained whether there were clean surfaces or not. Alloy steels were tested transversely; the imperfectly united surfaces lay across at right angles to the test-piece and at once showed up.

Another important point connected with the subject was that of hair-lines. In America serious difficulties with that particular class of defect had been experienced. Mr. Brearley adopted one of several theories that had been put forward, namely, that they were due to fissures. The root of the matter lay in those principles which Professor Arnold thought should be discussed in preference to details. No theory had as yet been accepted as to why blowholes should be produced and why non-metallic substances should occur in steel, and until some theory had been accepted it was difficult, as Dr. Arnold said, to discuss the paper. Personally, he had quite a different explanation to offer as to why the hair-lines occurred, but it was clear that in practice welding could not be effected by rolling.

Mr. E. H. SANITER (Rotherham) said there had been some rather loose talk on the subject, and nearly every speaker had accused Mr. Brearley of saying that a blowhole would not weld up. As a matter of fact, he had said nothing of the sort; what he said was that a blowhole would not weld up perfectly, which was a very different thing. Was there, indeed, anything that would weld perfectly? Some people talked of a weld from the point of view that it should be as perfect as a steel which had never had a weld in it. If a piece of wrought iron were treated in the same way that steel was treated it would break down under the impact test, showing that a weld in wrought iron, which was supposed to be the best welding material, was just as imperfect as a weld in steel, the subject which Mr. Brearley had been investigating. It might be the case, as stated by Mr. Whiteley and Mr. Cosmo Johns, that under special conditions a weld could be made that could not be torn apart. He was not at all sure on that point, but he was sure that if those special conditions did not exist any weld could be torn apart, whether it were wrought iron or steel specially prepared for welding or whether it was a blowhole in steel. In his opinion, the paper dealt more with sound steel than with welding, and its real point was that the author advocated a steel being made which contained no blowholes or, as far as possible, other things which would prevent continuity in the metal. On that point he thought the author was absolutely right. If that could be done every time

practice would be perfect. At the same time, there were certain articles and trades in regard to which it was almost impossible to prepare a steel of that description for the qualities required. He thought it was necessary to be very careful before any statement was bluntly made about the welding up of blowholes. One qualification which could be made was that blowholes did not weld equal to a material where there had been no weld, although they would actually weld up. Probably 80 per cent. of the steel made in Great Britain had been made from ingots with blowholes in them which had been welded up, and it served its purpose with great success.

Mr. C. H. RIDSDALE (Middlesbrough) said Mr. Brearley referred to the difficulty of getting thorough welds if a slag of the right fusibility were not obtained. It seemed to him (Mr. Ridsdale) a great pity that more common use was not made of powdered siliceous slags of low fusibility instead of sand for commercial welding purposes. It was well known that a great many commercial welds were made with no flux at all, but they ought always to have a flux, and if a siliceous slag of low melting point were used difficulty would not occur through the unequal amounts of sand and oxide of iron. Mr. Brearley had been called the champion of sulphur. That was hardly fair. It was very important that the effects of various bodies should be known, and, as Mr. Brearley said, it was "no part of an observer's business to allow personal prejudices or commercial prospects to colour his views." It was necessary to recognise the truth, and he thought all Mr. Brearley had been doing was to try to bring about a properly balanced view with regard to the effect of sulphur. What might appear as a defect under one set of circumstances became an advantage under another. With regard to the least harmful of the segregates being probably sulphur, it should be borne in mind that, just as during the war aliens were segregated in order to make them relatively harmless, so segregation of impurities made them, too, relatively harmless. In various steels there was not only sulphur but phosphorus in what might be called a "harmless" condition; it was separated out from the mass and in that state it did very much less harm, provided that the strains did not occur in the wrong direction for the segregate. With regard to the main point, he quite agreed with Mr. Saniter that it was not possible perfectly to weld a blowhole in ingots or to be perfectly certain that all the blowholes were always welded. When that state of affairs obtained it seemed to him that the mere fact that 70 or 80 per cent. were welded up did not very much matter, for 20 to 30 per cent. were not. Mr. Brearley had pointed out that if there were imperfect welding a crack going transversely across the mass would often be brought to a stop by it. It was well known that if there were a crack in glass a drilled hole would prevent that crack travelling. As, in wrought iron, there was a toughness transversely because of the fibre and the segregate, so, in steel, there was no need to worry too

much about whether or not the blowholes welded up, because if they did not weld up completely there were so many more points at which a crack would be arrested. To make a rather bold statement, he had always thought that if it were possible to obtain what the metallurgists called the ideal steel, absolutely sound and dense, it would be much more liable than the present commercial steel to cracks which, once formed, would go right through it.

Mr. J. E. FLETCHER (Dudley) wished to draw attention to a detail that had perhaps escaped attention in connection with Fig. 7, where along the alleged weld there was a continuous ferrite line, and also to the fact that all the welds that had been attempted had been imperfect. Looking carefully into the way in which the welds had been made, it would be seen that there was a mechanical reason for that difficulty. Mr. Brearley started with a 4-inch bar, plugged it, rolled it, and reduced it finally to a $4\frac{1}{2}$ -inch by $\frac{1}{2}$ -inch flat. In all rolling it had to be remembered that the interior of the bar remained hot while the outer surfaces were chilled by air and also by contact with the rolls, the hot centre of the bar being extruded, so that it slid past the outer portions. The extrusion of the centre portion of the bar over the cored centre largely explained the reason why Mr. Brearley did not get complete welding in any of the cases he had explained. If, for instance, a square section, plugged as described, were reduced to an oblong section there was a spread laterally and the two sides of the plug would be apt to be loosened, and at every pass there was a chance of a progressive loosening. He had had some experience of the making of what was called compound steel, the casting of a steel ingot in a mould containing bars of wrought iron and rolling down, and he had found in that composite material in almost all cases there was no such thing as a real weld between the different parts of the material. He did not think Mr. Brearley by his method was likely to get a perfect weld between the surfaces. The different rates of extension of the core bar and the surrounding metal also showed the reason why there was at the juncture of the weld and the remaining part of the ingot the ferrite line, the dragging of the portions of the ferrite along those slip-surfaces separating the two portions of the rolled bar. That slipping could sometimes be seen in wrought iron welds, but, owing to the included cinder, truly welded surfaces were possible if extension-slip were prevented by not too drastic working.

Mr. J. C. W. HUMFREY (London) said that in regard to hair-line cracks in nickel-chrome steels, he rather gathered that Mr. Brearley thought they were originally ingot defects. He himself had examined a good many of the fractures, and in no case had he ever found any connection between the line of the crack and the casting structure of the ingot as revealed by macrostructure and etching. In every case the hair-line crack had gone quite at random across the macro-

structure. That was rather against the view that the crack was formed in the ingot. Another point on the question of welding might be of interest. During the war a number of small gun tubes showed cavities near the muzzle. In the very finished state, the last stage of machining, the muzzle cavities were found large enough to allow of a finger being inserted. The tubes were about 4 inches diameter and were forged, so that the muzzle of the gun, where the cavities were found, came at the bottom of the ingot, and accordingly there was no question of pipe, and probably no question of blowholes either. He had been able to obtain a section of one of the ingots, which was found to be perfectly sound all the way down with regard to blowholes and piping.

Down the centre there was a series of very fine fissures, which were formed evidently by the final contraction of the ingot as it set. They went straight and parallel to the sides, but near the bottom they became conical. The tubes were forged with an enlarged end in order to get material for transverse test-pieces. Sometimes the end was removed and sometimes a portion left on, and apparently the cavities came somewhere about the junction at the enlarged end. In one locality, for example, there would be some chance of their closing up, but when defects were forged along another direction there might be a tendency to open them out, and he thought that was what occurred. With regard to the method of testing for welds by the Izod impact test, he thought that the impact test did not give really enough information, as there were many other factors coming into the Izod test which masked the whole effect. He would suggest to Mr. Brearley to try some of the tests by a slow method of notched-bar testing. In that case any defect which stopped a crack gave a very marked break in the curve. He had actually tested pieces in which in a stress strain diagram there was a sudden crack with an absolute stop, and then the crack went on again later. It was a very useful test in testing small welding defects.

The PRESIDENT said the fact which emerged from the discussion was that a welding was only an imperfect method of uniting two surfaces of metal. Mr. Brearley held that the gases in the blowholes, whether the cavities were or were not lined with non-metallic substances, were responsible for the imperfect welding-up of blowholes. Some time ago he (the President) had gone into that matter very fully, and had come to the conclusion that when a big ingot, in which the honeycombs were lined with sulphide, was rolled down to a rail or plate, those honeycombs would not perfectly weld but would do so if non-metallic inclusions were absent.

Cross-sections of rail heads made from ingots free from honeycomb, but which contained streaks of sulphide, broke at the sulphide lines on bending. The blisters which occurred in black sheets and other material tended to confirm Mr. Brearley's contention that gases might prevent welding. Fibrous steel could be produced by adding sulphur

and manganese to low carbon steels, which were strong in the direction in which they were rolled but were very weak in cross-section, fracture readily traversing in a longitudinal direction. Brinell obtained some of the best impact tests from steels which were highest in sulphur.

It was always necessary to take into consideration, when talking about shock or any other tests, the relation of the stress to the direction of the rolling.

He congratulated Mr. Brearley upon his paper and thought it would inspire more thought and more investigation, and that the net result would be a great advance in knowledge with regard to welding. He himself would like to have some information as to the effect of nickel and chromium and other impurities in steel upon welding properties. He had recently had a good deal of complaint about soft steel not welding, and in one case nickel was present to the extent of 0.12 per cent. and chromium in considerably larger amounts, and he was asked why that steel did not weld. Did chromium and nickel reduce the weldability of steel? It was a very important point and would have to be considered, in view of the fact that so much nickel-chrome steel scrap is now being used.

CORRESPONDENCE.

Mr. J. E. FLETCHER (Dudley) wrote further that most welds made by rolling methods were subject to the slipping and loosening action to which he had referred in the discussion on Mr. Brearley's paper, and it was extremely difficult to make a perfect weld unless the metal at the weld surfaces was prevented from flowing—a most difficult thing to bring about. In the rolling of wrought iron one of the most important points to watch was the design of the roll passes, so as to secure the effective welding of the surfaces between the bars of the pile. Old rollers would often maintain that the best bars were made by always rolling in one direction in old-fashioned "pull-over" mills. Their objection was fundamentally sound, though it had been questioned whether the quality-difference between bars in one-direction mills and those rolled in reversing-mills was sufficiently marked to warrant the condemnation of reversing-mills for iron-rolling.

Mr. Brearley's remarks on slag streaks and their effect on the prevention or restraining of crack travel were most interesting. Though he spoke of the fabled virtue of good wrought iron, it could not be ignored that such material contained within itself the very silicates which were acknowledged to be necessary to the efficient making of a weld. Further, it could not be denied that the boundary surfaces

of crystals of puddled iron were practically pure iron, whereas those of even mild steel were comparatively rich in unweldable carbide.

He (Mr. Fletcher) acknowledged that perfect welding was probably impossible in either iron or steel, mainly because of mechanical difficulties, but contended that, on Mr. Brearley's own showing, wrought iron inherently possessed properties which could not be approached by steel, the weld areas of which were so affected that the evil results could only be removed by careful heat treatment.

In the absence of carbide at the crystal boundaries wrought iron welds were not so depreciated, and the generally observed long life of welded iron cable made from normally treated wrought iron was evidence that welds of very high efficiency were possible and usual in such material, requiring no after heat treatment to correct the results of local heating.

Mr. Brearley had referred to the analogy between the ferrite line along the weld surfaces (see Fig. 7) and the ferrite banded structure in rolled steel plates. He (Mr. Fletcher) would further comment on his belief that that ferrite was the result of the differential slipping at the weld surface, the softer ferrite being dragged along the surfaces.

Similarly the differential flow of the successive layers of material from the cooled exterior to the hot interior might lead to a dragging of the ferrite along slipping planes in the direction of roll flow, banded ferrite being the result.

Mr. G. W. GREEN (Openshaw, Manchester) wrote that whilst Mr. Brearley stated that a perfect weld was a joining which was in all respects as good as any unwelded part of the same bar, he implied later that a perfect weld was one in which the two surfaces were absolutely joined together. That was an entirely different proposition. He concurred when Mr. Brearley stated that the presence of segregates accentuated the imperfection of the weld, and he would suggest that Mr. Brearley had unconsciously not taken into account the factor of chemical inhomogeneity in the consideration of the conditions of his ideal weld. That inhomogeneity was solely concerned with the gas content of the steel, and there was the possibility that that had a profound effect on Mr. Brearley's experiments. In those experiments the machined surfaces of the test-pieces would naturally have been exposed to the air for some time. There would consequently be a diffusion of air into those machined surfaces. No later operation, such as driving in a plug, or the short exposure of the surface to petrol vapour before sealing up the hole, would drive off the air which had diffused into the surface. Consequently the welding faces would have a higher oxygen and nitrogen content than the rest of the metal. On heating, the more or less complete solution of those gases would occur, and whilst the two surfaces were perfectly joined together on welding, chemical inhomogeneity had been induced, which would

exist as a film about the weld, and there would be a consequent difference in the degree of toughness of that film compared with the rest of the specimen.

In connection with the above suggestion it is interesting to note that Cathcart and others had observed that upon etching welds with Stead's cupric reagent a white line, following the line of the weld, invariably occurred. That white line would appear to be a segregation of dissolved oxygen.

He (Mr. Green) could instance a case in which a difference in the degree of toughness, caused by inhomogeneity, gave rise to a similar impact phenomenon to that recorded by Mr. Brearley. He had obtained fractures from some nickel-chrome steel ingots in the "as cast" condition. These were intercrystalline in character. When temper-annealed at 650° C. and slowly cooled, the resulting fractures were intercrystalline, thus showing that the grain boundary constituent had become much more brittle than the grains themselves. That effect was, incidentally, he considered, intimately connected with the phenomenon of temper-brittleness. From the chill crystals of a piece of ingot treated in such a manner impact test-pieces were taken, so that the notch was at right angles to the major axis of the chill crystals. When tested, those pieces invariably stopped the machine dead, the fractures having only gone part way through, and the chill crystals were torn apart from one another in exactly the same manner as Mr. Brearley's welds were torn open. Obviously the intercrystalline filling was so much more brittle than the crystals themselves that the test-piece might be considered as consisting of a number of separate crystals loosely connected together, and consequently the propagation of the impact fracture would be greatly hindered in having to overcome repeatedly the resistance of numerous fresh unnotched surfaces.

Mr. BREARLEY, in reply, wrote that some of the gentlemen taking part in the discussion, as Mr. Saniter pointed out, dealt with questions which were only remotely related to the subject of the paper. Two or three others, notably Dr. Rosenhain and Dr. Hatfield, regarded the author as the "champion of sulphur" and professed to see something "heroic" or "humorous" in the faint praise bestowed on the part played by that element as a constituent of steel. The amount of sulphur existing in commercial steels might be regarded as an indicator, as phenolphthalein was an indicator, of the effects of major reactions, the progress of which could not be followed by the eye; that was its most useful function. No good could come of repeating text-book information and unqualified traditional views, about the harmful effects of sulphur, which could not be supported by experimental evidence. The only question was whether statements made in the paper or elsewhere were true or false. The author would not be flattered by the support, nor depressed by the opposition, of those

who had not examined the question, as decisions would be made ultimately on evidence and not on authority.

Izod impact figures did undoubtedly represent only relative physical quantities, and their meaning could not be properly appreciated except in conjunction with the tensile strength of the steels to which they referred. Whether Izod impact figures used to measure weldability must also be tied to tensile strengths, as Dr. Aitchison suggests, was another question. Probably too little was known at present to justify a definite assertion either way. If Dr. Aitchison's assumption were correct it should be possible from a known welding figure of steel to predict its tensile strength and *vice versa*. Such a generalisation seemed premature and was in fact contradicted by the results obtained on steel "D," as approximately the same welding figure could be deduced from the steel whether tempered at 200° C. or at 450° to 500° C. Dr. Aitchison's indirect evidence of the influence of sulphur on the weldability of steel was interesting. He no doubt realised, though some others appeared to forget, that the surfaces pressed together to make a weld of a segregated part did not consist entirely of manganese sulphides.

It might be true, as Mr. Whiteley inferred, that air was not present in the blowholes of a solid ingot, but it certainly existed in some of those of a semi-liquid ingot. That the holes were bright and untarnished was no proof that air had never been in them. The torn open surfaces of the welds referred to in the paper were bright and untarnished, but Mr. Whiteley would, no doubt, object to that observation as proof of the absence of the air which, as he thought, made the results questionable. A variation in impact figures between 95 ft.-lbs. on a sound bar and 110 ft.-lbs. on a welded bar conveyed no clear meaning in relation to the welding figure as defined, viz., "the degree of toughness which must be induced in the steel before the weld can be pulled apart." Steels giving impact figures of the order of 100 ft.-lbs. were not broken on the Izod testing machine. They were partly broken and bent; whether the weld was opened or not depended on whether the welded surfaces came in the broken part or the bent part of the section. Thus a personal examination of the specimens might be convincing, but taken by themselves the impact figures were not convincing. Mr. Whiteley's contention that tests should be made after excluding the air was quite sound. More or less air was admitted but using no core and taking no precautions to drive out the air from the drilled hole; also by allowing the drilled hole to rust superficially. The results were not appreciably influenced by those great variations, although one must admit they did not prove that air was quite harmless. Mr. Green also raised a question of air having diffused into the machined cores, and evidently expected to find signs of it in the weld as a white band on etching with cupric reagent. The cupric reagent did not reveal a white band in any of the specimens. The impact values obtained on chill ingot crystals when tested along and across

their major axes were different, as Mr. Green said, the difference being due to imperfect cohesion and sometimes to actual cracks between the crystals.

Dr. McWilliam emphasised the importance of making use of what were commonly called defects. He would presumably use blown ingots or ingots containing non-metallics, whether sulphides or not, for purposes where those features could logically be expected to improve the durability of the steel, and where experience had shown that equal or increased durability had been attained. This was a common-sense view with nothing against it more serious than a nervous apprehension of departing from school knowledge which, once partly true, has under changed conditions become quite false.

Mr. Saniter and Mr. Ridsdale enforced the object of the paper by taking a practical view-point. While sound ingots were preferable for general use, there were purposes for which blown ingots were equally good and perhaps better. They might be better when stressed across the direction of rolling, and if so it was because the blowholes welded incompletely. It was not, therefore, possible to claim the improvement and maintain also the idea that blowholes welded completely. Mr. Ridsdale's idea that perfectly sound steel free from grain might be less satisfactory than existing steels was entertaining and could be supported by selected examples. Such a steel would be excellent for other selected purposes, and might ultimately be producible as heat-treated castings.

The author's intention in using cored billets was to reproduce ingot working conditions with a bias in favour of blown ingots. Mr. Fletcher's explanation for imperfect welds applied equally, if at all, to ingots and cored billets. If it applied at all one would expect the hot centre of a bar to be extruded to an extent depending on the length of the bar rolled. Experiments made on billets with sawn ends but varying in weight to such an extent that the heaviest was ten times as great as the lightest showed no variation in the shape and size of the extruded end. The end, as a matter of fact, was formed less by extrusion than by the manner in which the free ends "hit" the rolls on entering and leaving. It was equally doubtful whether ferrite lines were due to shearing stresses, as Mr. Fletcher suggested, because at rolling temperatures free ferrite did not exist. It might be argued that dissolved carbides were less concentrated in these positions taken up later by the ferrite bands, but such statements lacked proof.

The occurrence of hair-lines in crankshafts was undoubtedly due to different causes. The subject was discussed at several conferences arranged by the Air Ministry, and their reports summarised the chief causes. As, however, ingot cavities did not weld up, and no ingots were absolutely free from cavities, as also many crankshafts showed hair-lines in positions corresponding to the unavoidable "V" segregate cavities in ingots, the Air Ministry view that many hair-lines

were due to ingot cavities seemed reasonable. The special case quoted by Mr. Humfrey was very interesting, and no doubt Mr. Johns' experience would have been had time permitted him to express it less vaguely.

The author was indebted to the President for his earlier experiments on welding. These incited the author to re-examine the question, and he had received that help and consideration from the President in correcting false deductions, which the members invariably associate with Dr. Stead's amiable character and broad-minded love of truth.

Iron and Steel Institute.

THE SCIENTIFIC CONTROL OF COMBUSTION.

BY H. T. RINGROSE, B.Sc. (LOND.).

NOTHING is probably of greater importance in fuel economy than keeping a regular and systematic check either on the flue gases from furnaces where complete combustion is desirable or upon the evolved gas from gas-producers. It is not an uncommon thing to find producers working under similar conditions as regards fuel, yet varying in efficiency from 50 to 60 per cent., which means that one producer is burning 60 tons of fuel to produce the same amount of heat as the other is producing from only 50 tons. In some works samples of the gas are taken from the producer once or twice every twelve hours, an average sample from the main culvert every two hours, and the whole results tabulated and plotted each week. The cost of this system is only equal to a few tons of fuel each week, and if followed out by all would result in an astounding saving.

To secure a scientific control of combustion it is essential to know continuously the percentage of CO_2 in the gases. Nothing has shown the desirability of this more than the number of firms who have at some time or other installed CO_2 recorders. These instruments in skilled hands are a useful adjunct to a boiler-house and capable of giving good results. No one, however, who has visited a large number of industrial concerns can fail to be astonished at the number of cases one meets where the use of these instruments has been abandoned. That this fact is not peculiar to these islands is shown by the state of affairs existing in the States and on the Continent. The problem of recording the CO_2 automatically is a very difficult one and little success has been hitherto achieved. The old types of CO_2 appliances at the best can only be described as laboratory instruments, consisting as they do of a complicated mechanism quite unsuitable for the average stokehole work of to-day. The author is very glad to have the opportunity of bringing to the notice of the Institute an instrument for indi-

cating the CO_2 on an entirely new principle, and in no way resembling any of its predecessors.

In the course of experimenting with porous pots, fitted with a rubber cork through which passes one leg of a manometer tube containing coloured liquid (the difference in level of which in the two legs indicates the difference in pressure between the inside and outside of the pot), it was invariably found that the presence of any material inside the pot capable of absorbing moisture gave a persistent vacuum. On investigation it was also found that the amount of vacuum produced depended entirely on the amount of moisture in the air. An experimental demonstration gives the clue to an entirely new principle of gas analysis. Inside such a pot is placed a paper cartridge containing calcium chloride, which of course absorbs moisture. If the cork be replaced tightly a slight vacuum will in due course be produced and this will vary with the amount of moisture in the air. There is thus obtained a very simple instrument which shows the amount of moisture in the air continuously. The CO_2 apparatus consists of a porous pot inside which is placed a paper cartridge containing granules of soda lime. The lid is replaced and screwed down tightly. The whole unit is then placed inside a testing-box, into which can be put varying quantities of carbon dioxide from the gas cylinder, and the tube coupled up in connection with the inside of the pot to the manometer. After mixing the gas in the chamber a vacuum is gradually formed. A certain definite height of liquid will be given for definite percentages of CO_2 , and the accuracy of the measurement of CO_2 by this appliance even in a crude form is within $\frac{1}{2}$ per cent. To utilise this simple experiment for practical purposes all that is necessary is to aspirate continuously a sample of flue gas to the chamber containing the porous pot, which automatically measures and indicates at any instant the percentage of CO_2 surrounding it. The quickness or responsiveness of the indication depends solely on the porosity of the pot, which can be varied indefinitely. This phenomenon of obtaining a vacuum in a porous pot containing a suitable absorbent when enveloped by an atmosphere containing a gas which is being absorbed, and the fact that the amount of such vacuum depends solely on the percentage of absorbable gas surrounding the pot, are entirely new. By the adoption of

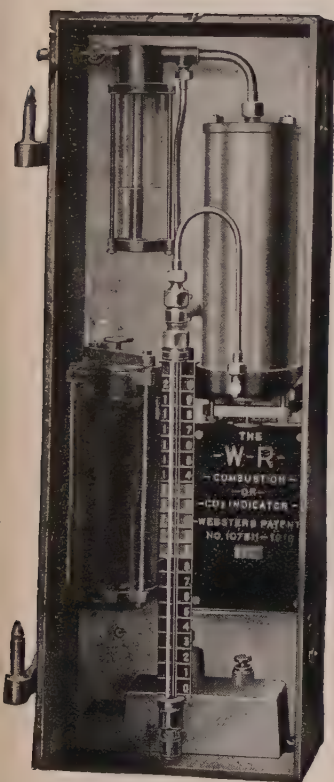


FIG. 1.

The W.R. Combustion Indicator.

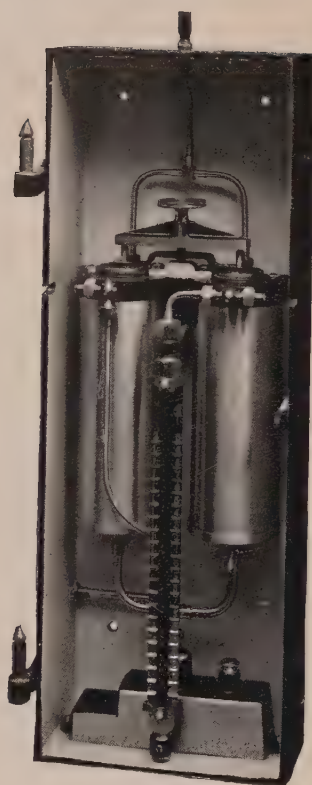


FIG. 5.

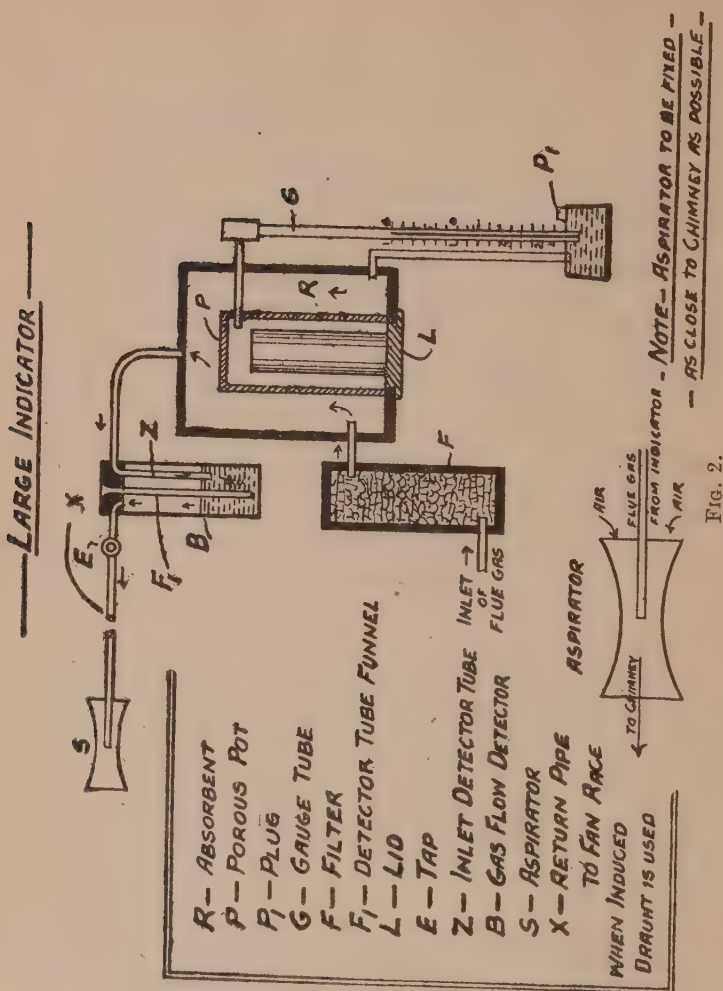
W.R. Producer CO₂ Indicator.

this principle many lines of research where gas analysis is of importance are opened out, although it is only with the question of indicating CO_2 that this paper deals. As an instance of the delicacy with which it is possible to work, the author has seen an instrument working on this principle indicating the percentage of CO_2 in ordinary air, that is about 0.04 per cent., and he foresees the time when such an instrument will be hung on the walls of theatres, music-halls, schools, hospitals, factories, &c., giving a direct indication of the vitiated atmosphere, the criterion for which is the amount of CO_2 .

Fig. 1 (Plate V.) shows the W.R. Indicator, designed to indicate the percentage of CO_2 continuously to the stoker. The range between 9 to 14 per cent. is marked in red to indicate where the level of the liquid should be kept. Some 1500 of these instruments have recently been supplied to leading firms in this country, the States, and the Continent. Many large generating stations have installed them on every boiler, the only possible system of ensuring continual efficiency from each unit. A high CO_2 content in the flue gases invariably signifies a highly efficient furnace with a high temperature and less smoke. A low CO_2 content indicates excess air passing through the furnace unconsumed, badly distributed fuel on the fire grate, thin fires or leaky brick-work. With attention to these defects the percentage of CO_2 can be greatly increased.

The course of the flow of gas through the instrument is shown in the diagram (Fig. 2). An aspirator S, worked by the natural draught which it increases, is fixed at a point as near the chimney base as possible, and continually aspirates gases from the flue it is desired to keep under observation. The path of gases is shown by arrows. They are first drawn through a filter F, and pass thence into the chamber containing the porous pot P, inside which is the dry reagent R. The flow of gas is shown by continual bubbling through water in vessel B. A pipe connects the chamber with a vessel containing water, into which dips one end of another pipe G, the other end of which is taken to the inside of the porous pot. As soon as absorption commences a vacuum is produced and the percentage of CO_2 is read direct from the gauge. The exact methods of installing these indicators are shown in Figs. 3 and 3A, from which it will be observed that

all piping is gravitated in order to prevent water-locks due to condensed vapour. Automatic water-traps are provided both at



the main filter and at the instrument for collecting the moisture in the pipe. The cartridge of absorbent should be renewed every twenty-four hours.

CONTROL OF PRODUCER FURNACES.

There is a very important field for such an instrument in furnaces where the products consist chiefly of hydrogen carbon

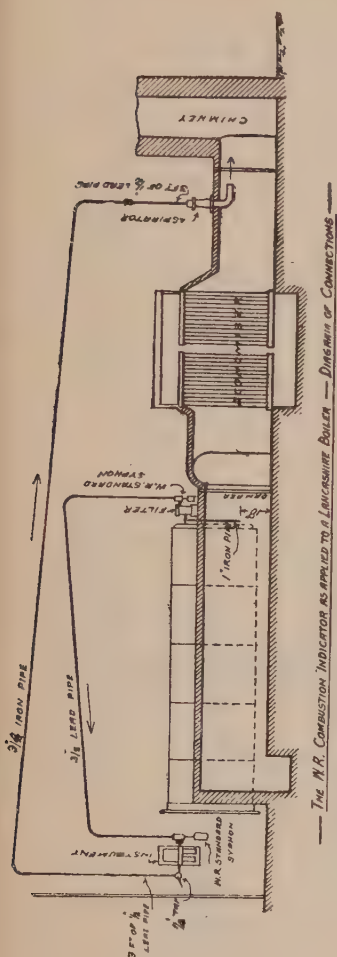


FIG. 3.

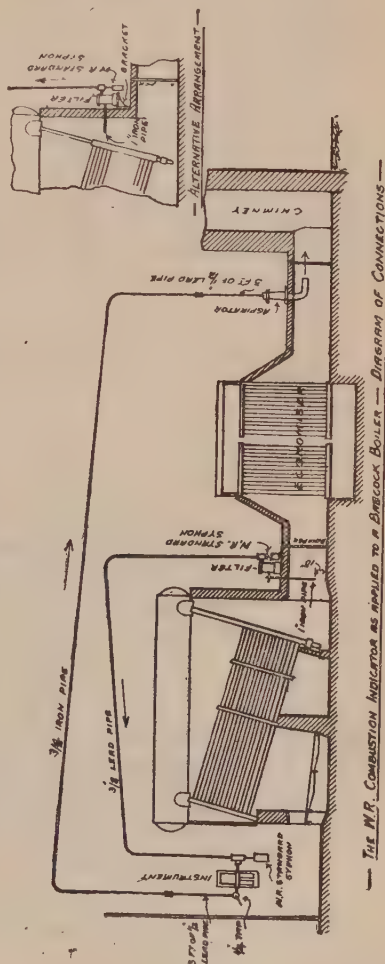


FIG. 3A.

monoxide, with a little CO_2 , and to which this new principle of gas analysis can be applied. The instrument previously described would not work accurately on producer-gas, owing to the presence of hydrogen. Almost everyone knows that hydrogen is a very

light gas, and that its molecules are able to pass through a porous wall quicker than air; hence the effect of sending producer-gas

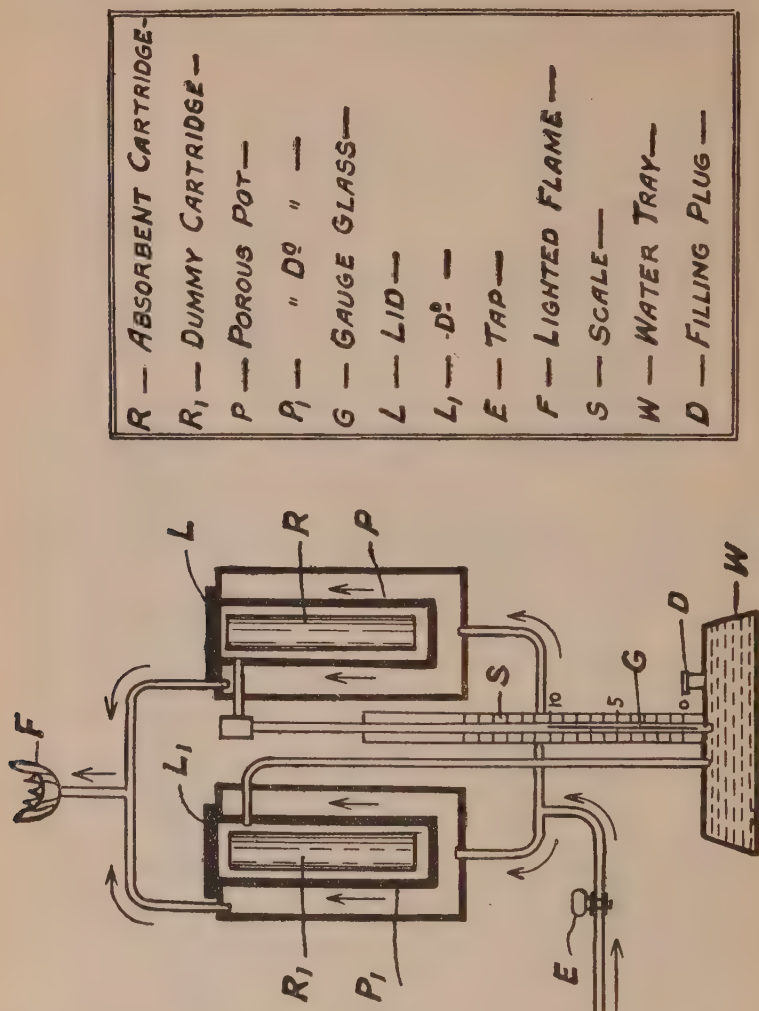


FIG. 4.

through the instrument described is to cause comparatively large pressures in the porous pot, hopelessly affecting the indications of CO_2 . This diffusion pressure can easily be overcome by the method about to be described. One porous pot is taken

containing an absorbent cartridge and another similar pot is provided with a dummy cartridge with no absorbent. If hydrogen be passed through, diffusion pressures are set up in both pots, but if these pressures be made to oppose one another, the effect of the hydrogen can be entirely neutralised, and the difference in reading on the manometer tube becomes proportional to the percentage of CO_2 in the mixture. The diagram (Fig. 5, Plate V.) shows the course of gas through the instrument.

This second instrument is known as the W.R. Producer or Water Gas CO_2 Indicator (Fig. 5). It has been thoroughly tested on a Crossley ammonia recovery gas plant at the works of Messrs. Crossley Bros., and the following results show the remarkable accuracy of the appliance, as compared with chemical analysis :

Date.	Time.	CO_2 per Cent. W.R.	CO_2 per Cent. Orsat.	Remarks.
1920. May 20th	3.30 P.M.	14.5	14.2	Test starting, 3.30 P.M. (20th).
"	4.15 "	15.5	14.8	
"	4.35 "	16.2	15.6	
"	5.0 "	16.5	16.5	
"	5.0 "	16.5	16.5	
21st	8.0 A.M.	14.5	14.2	Twenty-four hours' test, 3.30 (20th to 21st test continued after 24 hours).
"	8.30 "	14.5	14.4	
"	9.15 "	15.5	15.3	
"	10.15 "	15.5	15.5	
"	11.15 "	15.5	15.5	
"	12.15 P.M.	16.0	15.5	
"	1.45 "	16.5	15.8	
"	2.30 "	16.0	15.8	
"	3.15 "	16.0	15.8	
"	3.30 "	15.0	15.0	
"	4.15 "	15.5	15.2	
"	5.0 "	16.0	15.5	
"	5.45 "	15.5	15.5	
22nd	8.0 A.M.	15.0	15.0	
"	8.30 "	16.0	15.5	
"	9.15 "	16.0	15.6	
"	10.0 "	15.8	15.6	
"	11.0 "	15.0	15.0	
"	11.30 "	16.0	15.4	11.30 A.M. Test finished.

Plant shut down, 12 noon.

Total hours, 44.

Test Starting on 20th at 3.30 P.M.

20th to 21st at 3.30 P.M. 24 hours.

21st to 22nd at 3.30 A.M. 12 "

22nd at 11.30 A.M. 8 "

Total hours test 44 "

The usefulness of such an appliance as this on a producer need hardly be emphasised. Its use will enable the highest continuous efficiency to be obtained. Instead of working in the dark or even by the results of a few casual snap tests, there is a continuous indication of efficiency at any instant. It has been truly said that there is probably no factor of more importance to the successful working of Siemens or other gas-fired furnaces than the economical production of good gas, and a great deal of attention has been given to this by steelworks management. With the assistance of the W.R. Indicator the highest quality of gas can be ensured and the producer brought under direct scientific control.

CONTROL OF WATER-GAS PLANTS.

Although water-gas cannot claim in the iron and steel trade the importance of producer-gas, still, owing to its high calorific intensity, it becomes more extensively used each year for purposes where high temperature is the first essential, such as in welding processes. Its chief use is, of course, in gas works, where, after carburisation, it is mixed with the ordinary coal-gas from the retorts. The distinction between ordinary producer-gas and water-gas is that in the former a mixture of air and steam is passed continuously through the fuel bed in such proportions as will maintain its temperature conditions as nearly constant as possible, so that a gas of uniform composition is continuously generated. In the latter the two gasifying agents (*i.e.* air and steam) are admitted alternately, each for a definite period, and the products of the action of each are kept separate. In both cases gasification is complete, in one case uniformly, and in the other with alternating reactions. During the blow period, the percentage of CO_2 starts at a certain figure, depending on the temperature of the furnace. The CO being then at its minimum, as the temperature rises, the CO_2 decreases until a certain minimum is obtained, and the CO is then at a maximum. As regards the run period, the CO_2 at the commencement is very small, but rapidly increases as the temperature of the furnace falls due to the endothermic reaction with the steam. Thus, at any instant, the percentage of CO_2 is a direct criterion of the

stage the reaction, either in the run or blow period, has reached. To work a water-gas plant on truly scientific lines, the only possible way is to work to the CO_2 content in the gases. Assuming a means can be devised which will enable the CO_2 to be ascertained continuously, and with a few seconds only of time lag in the indication, it would be possible to have the plant brought under direct scientific control. The CO_2 Indicator, shown in Fig. 5, would not be nearly sensitive enough for this purpose. Its indication would only give the average value of the CO_2 in the gases from the run period, an indication which is, of course, valuable. Sufficient work has now been done on highly sensitive porous pots to convince the author that it is only a question of time and experiment before an instrument can be designed and made so sensitive as to show variations in CO_2 in a water-gas plant, almost second by second. When this is accomplished, water-gas plants can be run on truly scientific lines, based on the CO_2 content at any instant in the gases, and consequently on knowledge, at a glance, of the exact stage of the reactions.

CORRESPONDENCE.

Mr. J. A. C. EDMISTON (Hamilton) wrote that, in his opinion, the title of the paper would lead one to expect that there would have been undertaken at least a review of the author's typical observed points.

Again, whilst he fully recognised the importance attached to the use of the carbon dioxide indicating instruments, he could not help feeling that the author had put forward a claim for the use of an indicating instrument which could not be justified. Indicating carbon dioxide instruments were really of little value, inasmuch as they gave no record of the working of the plant to which they were attached. Recording instruments were of much greater value; they registered the results continuously on paper, which could be kept for further reference, and at the same time, when the men in charge of the plant knew that the results of their work were being marked down on paper, they paid better attention, indeed it had the effect of creating competition between the different shifts of men—that being so, the result was obvious.

From the indication on the chart it was quite possible to ascertain exactly when the class of fuel had been altered, or careless inattention for instance.

Tests for the percentage of combustibles were also made each shift on an Orsat apparatus and the reading on the chart was compared with the percentage of carbon dioxide obtained, the difference being seldom more than one per cent., and that was quite accurate enough for industrial purposes.

He (Mr. Edmiston) had considerable experience of different types of carbon dioxide recorders, and had found the Simmance, Abady, and Wood's patent the most reliable for industrial use. However, no manufacturer of those instruments had, so far, supplied an efficient filter for use with those instruments when applied to the control of non-recovery gas-producers.

In his opinion an efficient filter was most essential for the working of those instruments, and it was a pity that makers who supplied really good instruments should send them forth minus that most necessary accessory.

Mr. RINGROSE wrote, in reply, that Mr. Edmiston's criticism really raised the question of the relative values of a CO₂ indicator and CO₂ recorder. The author did not in any way decry the value of a recorder. On the contrary, he was of the opinion that in a great many cases such an adjunct was highly desirable. Every W.R. combustion indicator had special attachments so made that a recorder could be coupled up to it in a few minutes. Moreover, that recorder could be

placed anywhere within a reasonable distance from the stokehold, thereby ensuring the absence of dirt and dust, which in the past had played much havoc with the old and complicated type of CO_2 recorders. The author, however, could not help feeling that Mr. Edmiston was rather too eulogistic on the value of a recorder in these days when, as so often happened, a fuel specialist was employed to ensure reasonably high efficiency. A plain indication of the CO_2 in the flue gases then became essential, so that the conditions could be changed at that instant. To know from the recorder twelve hours after was just twelve hours too late, as the damage was then done. The W.R. combustion indicator had been designed to help the stoker, to teach him such essential points as the correct position of his dampers for various thicknesses of fire-beds. Moreover, when fixed on every boiler a healthy competition arose between the firemen. The author submitted that the ideal arrangement of CO_2 appliances in a stokehold was to have indicators on each boiler, and a recorder on the main flue, preferably placed in the engineer's office.

Iron and Steel Institute.

NOTES ON THE CLEANING OF BLAST-FURNACE GAS.

By S. H. FOWLES, A.M.INST.E.E., A.M.I.MECH.E. (JARROW-ON-TYNE).

WHILE the broad factors of fuel economy are fairly well understood there are a large number of what may be termed hidden losses in various industries which collectively amount to a considerable waste. It is on the subject of one of these sources of loss that the present paper has been written, more particularly from the point of view of the heat and power economy possible as the result of more efficient cleaning of blast-furnace gases. The present paper describes a plant erected at Messrs. Palmer's Shipbuilding and Iron Company's works in the early years of the war under very trying circumstances, when material and labour were very hard to obtain. Within about eighteen months this plant was got to work. It was estimated to be capable of cleaning gas to develop about 27,000 horse-power from crude waste gas. It ran continuously for another eighteen months with 20 or 30 per cent. overload, and was indeed one of the main factors that helped in the production of munitions of war. During this period many difficulties incidental to the continuous running of an entirely new plant had to be dealt with as they arose, very little information being available to guide those in charge.

In 1913-14 the first German gas-cleaning plants were being installed in this country. At the outbreak of war they were still unfinished, and the departure of the German engineers engaged on the works left the latter without the data and guidance necessary for the successful completion and operation of the plants. In these circumstances the work had to be carried out with great caution: much of the original theory had to be discarded and fresh theories evolved from data obtained under actual working conditions, in spite of velocity and quantity of gas being high and changeable. In the result there are, to the great credit of British works, plants working at the present day as well, if not better, in this country than in Germany.

The first thing to be done was to endeavour to ascertain the

inventor's intention and the ideas he had at the back of his mind so as to apply them to the operation of the plant. After this had been done it was found that several factors were not working out as expected. The gradual improvement of the plant and practice were the next steps. This having been effected the plant is at the present time being operated in a manner very different from the original practice, and incidentally a great many worries and troubles have been overcome. It is in the hope that the data acquired may be of help to others, and that a still greater field may be opened up for the application and improvement of gas-cleaning practice, that this paper has been written.

The following are some of the many reasons why blast-furnace gases should be cleaned thoroughly and used efficiently :

1. There is a most productive field for the recovery of potash from the dust taken from the crude gas. This should tend to stop the import of potash to this country.

2. It is possible to-day, if the gases be well cleaned and efficiently used, to produce something in the neighbourhood of three to four million horse-power from the waste blast-furnace gases of this country, in addition to reducing large coal bills, speeding up works, and undertaking much of the work now done by coal-fired boilers.

3. It would be possible to supersede the old steam-driven blowing-engines, and render blowing by large and efficient gas-driven engines an easy proposition.

4. The electrical equipment of large works can be developed on a larger scale and at lower cost than was ever anticipated.

The subject is dealt with under the following heads :

1. The gas and its contents ; old and new methods of using it, and the advantages to be derived therefrom.
2. The Halberg-Beth dry gas cleaning plant ; old and new methods of operating it, and some reference to competitive plants.

The data accumulated are given in tables in the Appendix.

GAS AND ITS CONTENTS.

The gas, heavily laden with dust and moisture, passes from the furnace tops into large cylindrical dust-catchers, where about

20 per cent. of the larger particles of dust is deposited. This portion is of very little use for the recovery of potash, the greatest amount being found in the smaller and finer dust which is carried by the gas through a zigzag main to the cleaning plant, where the gas is finally divested of its dust and of most of the moisture.

The constituents of the gas are given in Table I. in the Appendix, and are an average of several plants taken over a period of about one year. It will be seen that very little variation occurs in the constituents, and therefore in the B.T.U.'s per cubic foot. One great advantage arising from this is that engines can be set (*e.g.*, air and gas throttles adjusted) which gives good running and constant load. An average temperature of the gas leaving the furnace is in the neighbourhood of 500° to 800° F. This drops to about 500° F. in the zigzag main, which is about 8 feet in diameter, and leads to the cleaning plant. The function of the above main is to change the direction of the gas as often as possible and so deposit the larger particles of heavy dust and considerably to cool the gas.

The average of many blast-furnaces in this country has been taken, and it has been found that the production of gas is approximately one million cubic feet per furnace per hour under ordinary working. Hitherto the whole of this gas has been consumed by the furnace auxiliaries, and in addition a large amount of coal has been burned for steam-raising purposes for the blowing.

The whole of the potash was lost, as the dust was regarded merely as a nuisance. Flue-cleaning was a very expensive item. An average has been found to show that the crude gas under the above conditions was consumed as follows :

The hot stoves consumed about	40	per cent. of the gas.
The boilers	60	„ „ „ „

The latter on an average only provided something in the neighbourhood of 1200 horse-power for the blowing of each furnace, while 40 per cent. of the gas was consumed to heat up the cold-blast from the blowers before entering the furnaces. How inefficient this method was will become more obvious later.

MEASUREMENT OF GAS QUANTITY.

This was one matter that had to be dealt with in the very early stages; the old method was to calculate the volume from the quantities of coke, &c., used. This served its purpose, gas being generally used *ad lib.*, and so long as everyone got sufficient no one troubled about quantities, but with the advent of the new methods and records a new basis had to be provided from which the amount of gas passing could be ascertained in a few minutes.

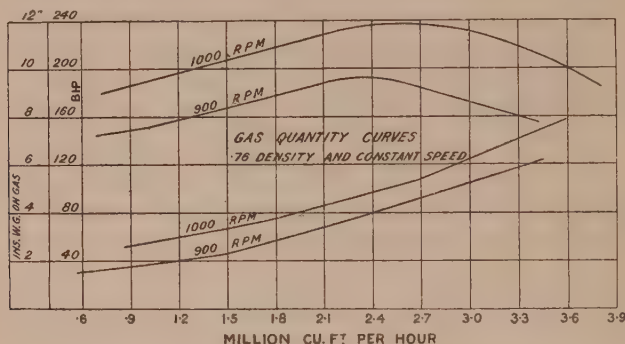


FIG. 1.

This was done by means of a set of curves as shown in Fig. 1. These were plotted by the author and the makers, and are, with slight modifications, easily adaptable to any fan working on either this particular gas or any other gas. When it is known that the gas density and temperature are fairly constant at the fan, and the fan is running at a constant speed, the only necessary factors to be sought are the horse-power of the motor, the water-gauge pressure of the gas at that instant, and the motor speed. The curves have been checked in several ways, and the error found to be negligible. The various curves are for different speeds.

The old method was a lengthy one, and is given in the Appendix (Table II.). It will be seen that it is too long for everyday operation. It was thought to instal a Venturi meter, but should gas of say 0.01 gramme of dust per cubic metre pass the error

of the meter would be considerably increased and a wrong reading obtained.

The gas passes to the gas-cleaning plant by way of the zigzag main, and is divided up after cleaning, one main leading to the boilers and hot stoves, where about 1,386,000 cubic feet of gas per hour was consumed under the old conditions. This was the first use that was made of cleaned gas. The results were that the hot stove temperatures were increased from 800° F. to 1100° F. and the make of pig iron increased by 10 per cent., the coke for the furnaces being reduced 250 tons per week. The coal to boilers was reduced from 200 tons to 20 tons per week. The financial results are tabulated below :

250 tons of coke saved at £1 10s.	.	.	.	£375
180 „ coal „ £1 5s.	.	:	.	225
Total				£600 per week
Less wages on gas plant	.	.	.	£47
Energy for motors, &c.	.	.	.	13
Stores and repairs	.	.	.	20
Total				£80
Saving per week	.	.	.	£520

The gas produced to-day is about 3·5 million cubic feet per hour and is used in the following manner :

	Cubic Feet per Hour.
Hot stoves for blast	1,056,000
Boilers for hoist and auxiliary plant	400,000
Gas blowing-engines of 5000 horse-power, total	500,000
Gas-driven generating engines of 8500 horse-power	850,000
Not required	700,000
Total	3,506,000

It will be seen from the above that with the same quantity of gas made, 8500 extra horse-power is being obtained with considerably less labour. This figure of 8500 horse-power will, it is hoped, in the very near future be increased to about 12,000 horse-power, and the plant has been arranged with this object in view.

The power supply for the whole of the works, which was previously bought, amounts to 88,000 kilowatt-hours per day,

costing a little over 1d. per unit, and is now being produced entirely from waste gases at about 20 per cent. of the unit cost.

This is entirely due to the new method of gas-cleaning, which allows the gas to be used for engines. Indeed, the gas is found on inspection to be, on an average, cleaner than the atmosphere in the particular district in which the plant is situated.

The plant on first starting was supplying boilers only for a period of six months. After this the hot stove burners were converted for clean gas, and were then supplied with clean gas. This gave a period of two months with all boilers and stoves on clean gas. Following this, a portion of the gas-driven blowing-engines and generating engines were started up and a large portion of the boilers shut down. The boilers have now been entirely dispensed with for power purposes.

THE USE OF GAS FOR BOILER FIRING.

This has been a general practice in this country but has nevertheless been very inefficient. Earlier in this paper it will be seen that 636,000 cubic feet of gas per hour were going to boiler-firing to raise steam for power purposes, the total load being only about 1200 horse-power. Now $636,000 \times 100$ B.T.U.'s per cubic foot equals 63,600,000 B.T.U.'s per hour, and if efficiently used by gas-engines should develop about 6500 horse-power as against 1200. This shows that gas under boilers is only about 20 per cent. efficient, as compared with the efficiency of large gas-engines.

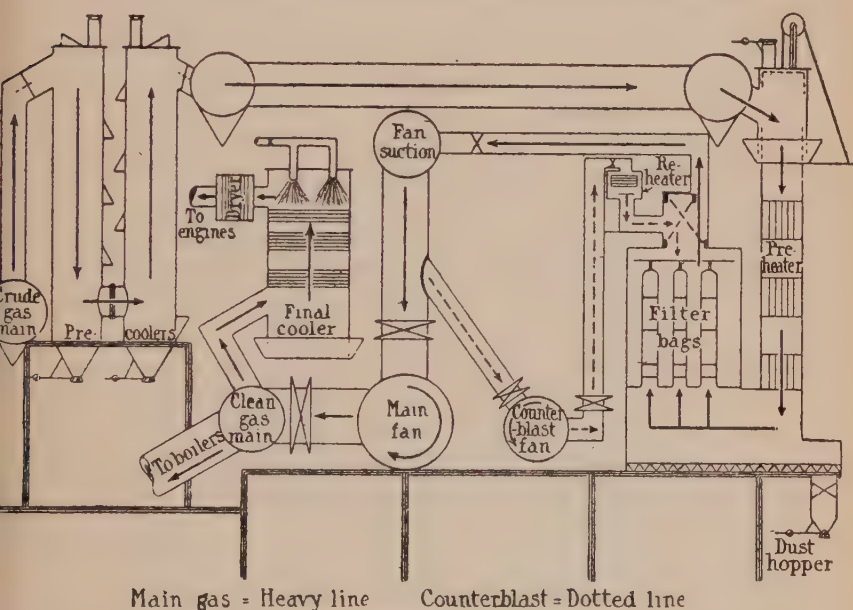
It is pleasing to know that the days of the above practice are numbered, and although there are many places where this practice is still in operation, they must soon be stopped if progress is to be made, and this country is to compete in the open markets.

The progress on the gas-driven electric sets is a striking result of what can be done when the total works cost per unit generated is taken at 20 per cent. of the price per unit bought. This alone is a tremendous saving, and should be very carefully investigated by all who are to-day wasting, or inefficiently using gas of any description.

GAS-CLEANING PLANT.

A sketch of the gas plant and of the path of the gas is shown in Fig. 2. The main gas passages are shown in heavy line, while counterblast course is shown in dotted line.

Commencing at the crude main, large uptake mains convey the gas past butterfly baffles to the top of the dry coolers, which



Main gas = Heavy line Counterblast = Dotted line

FIG. 2.

have four annular tubes passing vertically through them. The intention was for the air to take up heat from the gas and cause a continuous flow of air up the tubes owing to the increased air temperature, but when it is remembered that the hottest gas enters at the top of the coolers and has a downward path, obviously the circulation is partly destroyed. An arrangement of water-sprays has been arranged down the whole length of tubes, and a considerably greater cooling effected.

The drop by air was 15° C. The drop by water is 40° to 45° C. We are now obtaining much better results by forced air cooling in these tubes,

The gas passes from the dry coolers above-mentioned to wet coolers of the same diameter and length, but with no inner tubes ; they are fitted with two rows of internal sprays. The gas takes an upward path, and the coolers were designed for the water to cool the gas and drop a considerable amount of dust by the dust becoming laden with moisture. This was found to be the wrong principle from beginning to end, for the following reasons :

1. The dust particles are very small and contained a good percentage of potash, which was being carried away by the washing.
2. The water was carried on by the temperature and velocity of the gas to an extent of about 6 per cent. of the water introduced into the coolers.
3. This water considerably raised the dew point of the gas.
4. It necessitated the raising of the gas to a higher temperature in the pre-heater, before entering the bags to avoid moisture deposit.
5. It gave rise to condensation in the dust hoppers, and reduced the percentage of potash in the dust. It also gave rise to spontaneous combustion of the dust which was caused by the moisture coming in contact with the lime, and small particles of coke and carbon remaining in the dust.

The original German practice was completely to cool the gas by internal water, which, apart from destroying the potash, completely coated the filter bags at the first experimental plant in Germany. It is for the above reasons that internal water has been completely condemned, and all available external cooling resorted to. The ideal conditions for the operation of the plant is to lower the gas to a safe point ; to drop say 80 to 90 per cent. of the moisture content, and then reheat the gas so as to allow it, on leaving the fans and being put on the clean gas main for service, to be not lower in temperature than when leaving the coolers, otherwise the moisture may be dropped.

The temperature of the gas-house containing the filter-bags should not be below the dew point of the gas, or condensation will occur inside the boxes. As it is so essential always to avoid

the dew point of the gas, several curves for the purpose of obtaining the dew point are given in Fig. 4.

Fig. 3 gives the amount of moisture contained by gas at various dew point temperatures. The curve also gives the dew point at that temperature and saturation. This is of great importance to all plants dealing with gas. By turning the curve so that the base is formed by the temperature, the moisture that can be taken out of the gas for any temperature drop below

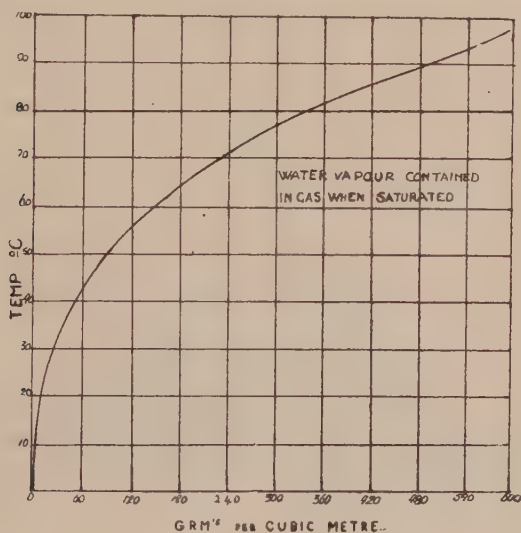


FIG. 3.

the dew point can be read off on the abscissa. This again goes to disprove an old theory which originated in German plants, that no moisture was dropped until the dew point was reached. This has been proved incorrect, as during one test moisture was dropped at 20° C. above the dew point of the gas, owing to the apparatus containing gas at a temperature below dew point.

It further proved that the most efficient and effective way for cooling gas is to draw it out at a low pressure, and so gain the full effect of skin cooling. .

During the above tests the temperature of the gas was taken at several positions in a 4-foot main, and a difference of 100° C.

was noted between the outside layer and the centre of the tube. This gas was passing the centre of the tube with a velocity of thirty miles per hour and under a pressure of 2 inches to 3 inches water-gauge. This was the first step that led to the cooling of gas by drawing it through the coolers and not allowing the coolers to be under pressure. This considerably reduced the tempera-

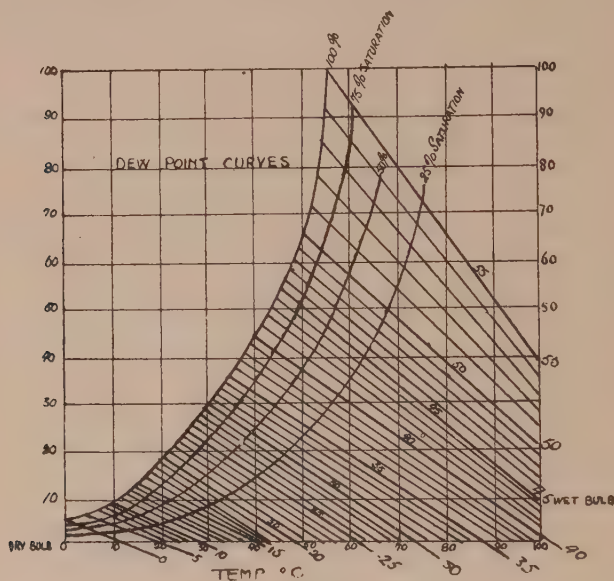


FIG. 4.

ture of the gas to be dealt with, and was found beneficial to the plant in many ways.

One great benefit derived from this state of cooling is that the drains provided for draining mains, valves, and fans at many points of the plant are not required, and so prevent a plentiful source of water lodgment, which would be a great disadvantage to the plant if neglected and the water allowed to flow back, due to heading up, or if the drains became empty and a large amount of gas escaped into the house, or an equivalent of air was drawn into the plant, depending on pressure or suction on the plant.

Fig. 4 gives a set of curves which enables the dew point of

any gas to be found from the following rule, the wet and dry bulb thermometer readings being taken.

Take the dry bulb on base line ; proceed vertically, until the wet bulb temperature is cut. From this point proceed along the horizontal line to 100 per cent. saturation curve. Immediately under this read dew point on base line.

The wet and dry bulb thermometers are both inserted in an india-rubber cork about $1\frac{1}{2}$ inch diameter, the wet bulb being moistened by a thin strip of muslin attached to the bulb and connected to the water supply outside the gas compartment. It can be permanently fixed in the plant and read by the attendant at any time.

Too much importance cannot be attached to the hygrometric operation of the plant if satisfactory results are to be expected. It is now possible to get a dew point with blast-furnace gas as low as 15° C. This corresponds with 59° F. and is quite a reasonable temperature.

With a dew point of 40° C. = 104° F. it becomes necessary to run the plant-house at 115° F. = 46° C. to avoid condensation inside the plant proper. The skin of the gas has been proved to travel at a much slower rate than the inner layers, and so be more subject to moisture deposit.

The cause of the low dew point of 15° C. is the complete abolition of internal water cooling, and a very low temperature of gas leaving the coolers ; it naturally follows that the lower the temperature the gas is taken to in the coolers, under dry conditions of cooling, the more moisture will be deposited. This is also assisted by the following conditions : the coolers being provided with baffles on the incoming side, full advantage has been taken of these by arranging all on one main turning shaft, so that the operation of all baffles is simultaneous from inside the gas-house.

This enables the coolers to be kept under a very slight suction from the main fans, as after numerous experiments it was proved that gas under positive pressure could not deposit dust as easily, and consequently as quickly as gas under expansion. This method has therefore been resorted to with very favourable results, both as to moisture and dust deposit.

In order to obtain these results the makers' established practice

has been departed from, and instead of atmospheric pressure being maintained at the pre-heater bottom it has been applied to the cooler outlet main.

At first sight it would appear that this would increase the fan suction on the bags. Although this has happened to some slight extent, the filtering of the gas is carried out under better conditions, and the fan suction is generally $1\frac{1}{2}$ inch below the makers' figure when the plant is working on 20 per cent. overload. This has proved in practice that the method should be to draw the gas through the filter bags, and not to push it through by a heavy crude gas pressure. This considerably increases the life of the bags, which is given by the makers as six months. Bags have been taken out in very good condition after fifteen months' continuous service. The average bag changing is about five per week out of a total of 792. It will be seen that some bags may reasonably be expected to last two years. The counterblast quantity which is continually being cleaned and blown through the bags completely to remove the dust from their inner surface is of great importance. Under the makers' figures it was found to amount to 15 per cent. of the total gas cleaned, a figure which considerably increased the plant losses.

After careful consideration and tests of the above methods of operation, it was found capable of reduction to 8 per cent. of the total gas cleaned. This alone has a considerable bearing on the life of the filter bags, in addition to keeping the atmosphere of the whole house in a much more healthy state for the operating staff, and reducing the power consumed by the fans.

It may be said that too much care and attention can be given to such a plant, but it has been the author's experience that to investigate carefully every part of the plant, and to lay down rules based on the experience gained by such investigations, have invariably led to tests of further importance being taken. Under these conditions the Halberg-Beth dry gas cleaning plant becomes a healthy and prosperous undertaking.

As the plants generally have to be run by unskilled labour it becomes essential to omit all calculations, and wherever possible to instal a recording gauge for temperatures, pressures, &c. With this end in view, it is considered that a dew point recorder would be a very useful instrument, with the result that several

schemes are in progress for installing such an instrument. As this is the most important factor in the plant, it has proved beyond doubt that the essence of the operation of the plant is to be found in the pre-coolers, and that, given correct ideals at this point, the plant itself and all filter bags, &c., work almost automatically. This will be seen from a set of curves produced

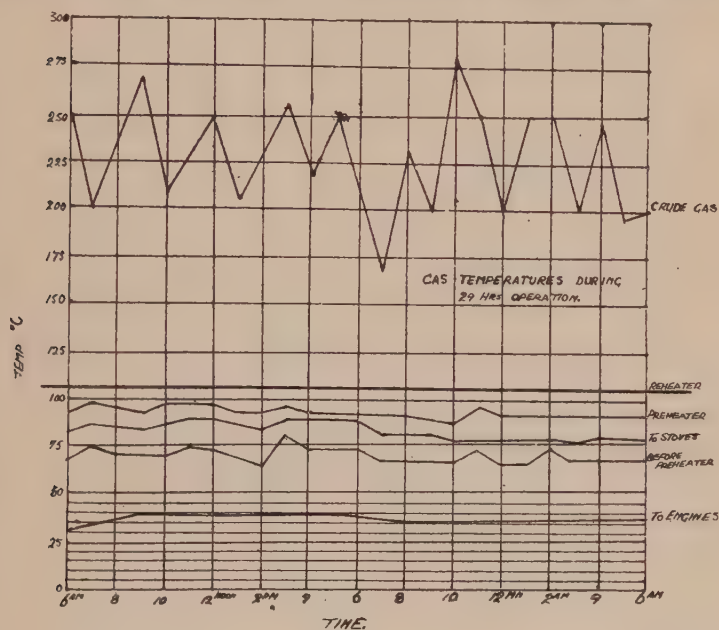


FIG. 5.

giving the temperatures on the various portions of the plant (see Fig. 5). The peaky crude gas temperature will be noted, and yet that, with a constant supply of external water to the coolers, the clean gas temperature is kept very constant. This is due to automatic baffling on the coolers, which allows the gas to be drawn out in the coolers, and the natural cooling considerably increased, which is absolutely essential when dealing with a gas at say 250°C . When this gas has to be dropped to 80°C , a drop of 170°C occurs before entering the pre-heaters.

This last paragraph alone will show the great importance of dry cooling, as under these conditions it is an acknowledged fact

that the dew point is always being reduced, which should occur all through the cooling process. With water injection the dew point will be raised considerably, and if this happens the uneconomical zone is rapidly approached.

The coolers shown in the sketch are very economical for cleaning and working and are to be preferred to economisers, owing to the larger area for dust deposit and the assistance of natural cooling.

One set of coolers can be closed up and cleaned out in a few hours without any interruption to the working of the plant.

Fig. 6 shows the present and the ideal methods respectively of operating the plant by temperature.

The conditions obtaining under the general accepted system are not capable of giving a low dew point, owing to the large amount of water injected into the gas at the wet coolers. This is in the neighbourhood of 4 grammes per cubic metre with inside water used at the rate of 204 grammes per cubic metre of gas cooled, and is capable of increasing the dew point by 2°C . Should the total cooling water allowed be used this would amount to 550 grammes per cubic metre of gas cooled, and would be capable of increasing the dew point by 5.4°C . Under these conditions the plant-house has to be kept at a fairly high temperature to ensure the total drop through the plant being small and yet remain above the gas dew point.

The only advantage of this method of cooling is to leave a large amount of sensible heat in the gas to pass along to the boilers and stoves. This is not true economy, as a drop of 69 per cent. of the temperature is lost (in some cases) in the travel to the boilers and stoves, consequently a large amount of water is deposited. It can therefore be assumed that a fairly dry gas is being supplied to the boilers, &c.

In this case the following conditions prevail :

The gas supplied to the engines has to be in the neighbourhood of 15° to 20°C . in order to get a very dry gas and also to increase the density of gas, or in other words, the gas, if increased in density and perfectly dry, will conduct the maximum B.T.U.'s to the engines. It has been noticed under tests that with a cool dry gas an increase of 10 per cent. load has automatically been taken up by the engines.

A final cooler and dryer are usually arranged for this purpose to lower the gas temperature, so that it will be seen that part of the gas is delivered to the boilers partly saturated for the purpose of still holding sensible heat, but this is lost by the gas cooling to such an extent as practically to destroy the whole of it, so that no useful purpose is obtained. The other portion of the gas is passed through the final cooler and dryer to the lower tempera-

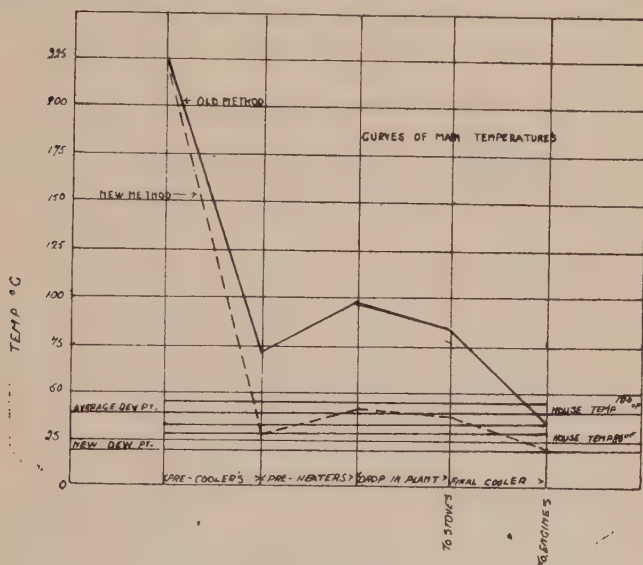


FIG. 6.

ture for the engine consumption, so that the primary object is defeated, *i.e.*, to hold sensible heat.

This brings us to the ideal conditions, namely, to increase the natural and external cooling to obtain the resulting temperatures shown in Fig. 6, before cleaning the gas.

Under these conditions :

1. The gas is lowered to a point approaching a dew point of 15° to 25° C., which will ensure a greater amount of water being taken out of the gas at the pre-coolers.
2. The pre-heating will be considerably less, and reduce the steam consumption at the pre-heaters by approximately 50 per cent.

3. The drop in temperature through the plant will be less.
4. The fans will deliver more gas if required.
5. The final cooler will have no work to do.
6. The gas will be dryer passing to the engines, and the temperature of the plant-house will be lower, and therefore the plant will be more fool-proof.
7. The final cooler for cooling the gas for the engines can be used on the pre-coolers, and do its work in the correct place, *i.e.*, before the gas enters the filter bags and not after.
8. A considerable saving would follow the steam saved in the pre-heaters.
9. A much better filtering would be obtained at the bags, owing to the gas and dust being dryer, and the temperature lower.
10. The mains would be cooler, and consequently dryer and cleaner.
11. The coolers being kept dry inside would be considerably cleaner, and so always offer a maximum cooling surface.

TESTS FOR COOLING.

On several tests taken with the gas passing at 250° C. the container was found to be dry, and in passing on through a set of pipes and tanks the following conditions were noticed :

At the point where the water was injected the tanks and pipes became completely clogged up ; the gas being then at a temperature above its dew point (the atmospheric temperature being below its dew point, which was 38° C.), moisture was deposited in the pipes, showing that the amount of water has been dropped to correspond with that dew point (see Fig. 3).

After this point, and before pre-heating, the pipes were found clean and dry, and the dew point lowered to 32° C. This indicates the ideal system of dropping the maximum amount of water out by a dry process of external water or natural cooling to a dew point of 15° C., when the maximum amount of moisture contained will be only 13 to 14 grammes per cubic metre. It will be noticed from the inversion of this curve that the lower the temperature of the dew point the greater drop necessary to take out a corres-

ponding amount of moisture ; therefore a tremendous drop could be tolerated in the plant, and yet the gas be quite safe from moisture deposit.

This proves the necessity for a fool-proof plant and for the whole operation being considerably improved.

SUMMARY.

The foregoing shows that the following points require very careful investigation :

1. Waste gas and heat must be used at the maximum efficiency. This has not been done in the past in this country, but has, to a large extent, been more efficiently practised on the Continent and in America.
2. To use the gas under boilers, whether from coke-ovens or blast-furnaces, is a barbarous practice. Therefore we must cultivate the internal combustion engine. This must be borne in mind when selecting a cleaning plant and all the details must be taken into consideration carefully. The internal combustion engine is fast proving its value as an economical and reliable prime mover and is improved considerably when supplied with clean dry gas.
3. This means that the crux of the whole business rests with the gas-cleaning plant, which has been proved beyond doubt to be the case.

Gas-cleaning plants for cleaning blast-furnace gas are of several types :

1. The wet process.
2. The dry process.
3. The electrostatic process.

Dealing (1) with the wet process : r

It must first be assumed that boiler firing is out of the question, and that for engine consumption there must be a reasonably dry, clean gas, but the gas from a wet cleaner must of necessity be fully saturated at the temperature of leaving the washer, and will give much higher maintenance costs on the engines. This

type of cleaner has therefore some disadvantages when considering future progress.

(2) The electrostatic type of cleaner is comparatively new, but so far the power costs of running and the capital costs are very high. The one main feature of this cleaner is that the gas after cleaning contains the whole of its sensible heat. If it be assumed that boiler firing has been provided for this feature is lost. Secondly, the gas after cleaning is not in a sufficiently clean state to be used in engines, and must pass through some other type of cleaner before being fit for such consumption, unless still heavier maintenance costs are to be incurred.

(3) The dry process is neither a "dry hot" nor a "cold wet"

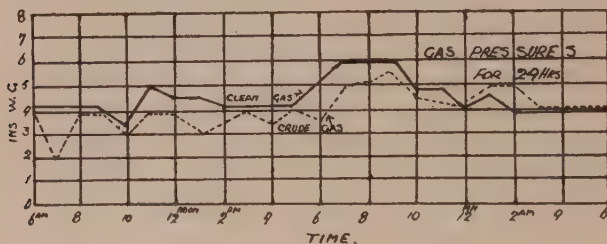


FIG. 7.

process but stands between the two, and while possessing all the advantages required by the gas-engines has so far proved to be free from the objections of the two previous types, and is an ideal plant for cleaning gas for engine consumption. It is moderate in first cost, economical to maintain, easy to operate, and flexible in respect of furnace operation. It gives a clean dry gas for the engines, and a clean dry gas of reasonable temperature for stoves and industrial heating (see Fig. 7).

A continuous gas supply is maintained when the fans are accidentally stopped, the engines continuing as usual without any interruption. This record has been maintained over a number of years, and engine maintenance found to be very low.

In conclusion the author considers blast-furnace and coke-oven owners should be encouraged by engineers to work for a maximum efficiency on the stoves and a maximum surplus of gas for the generation of power, which would thus become a great national source of cheap energy.

APPENDIX.

GAS CLEANING PLANT.

*Details of Areas, Volumes, and Surfaces.**Crude Gas Main.*

Diameter = 8 feet 0 inches.

Gas temperature = 280° C. to 150° C.

Y Mains between Coolers and Plant.

Cooling area, 5304 square feet: drop = 15° C.

Dry Coolers.

Height = 57.25 feet.

Diameter = 10.0 feet.

Volume = 4523 cubic feet—724 cubic feet = $3799 \times 5 = 18,995$ cubic feet.Air-cooling area = 1868×5 9,340 square feet.Water-cooling area = 1444×5 7,220 "

Total area = 16,560 square feet 16,560 "

Drop on gas = 48° C.

Gas passing per hour = 700,000 cubic feet per cooler.

Water used per cooler = 640 gallons per hour.

Water temp. in = 13° C.

" out = 36.5° C. Rise = 23.5° C. in water.

Gas temp. in = 188° C.

" out = 140° C.

Total water used on five dry coolers = 3200 gallons.

Total area of filter bags = 16,632 square feet.

Wet Coolers.

Height = 57.25 feet.

Diameter = 10.0 feet.

Volume = 4523 cubic feet $\times 3 = 13,569$ cubic feet.Cooling area = 1868 square feet $\times 3 = 5,604$ square feet.

Drop on gas = 55° C.

Gas temp. in = 140° C.

" out = 85° C.

Gas entering plant top = 70° C. Cooling on Y main = 15° C.

Gas passing each cooler = 700,000 cubic feet.

Water used per cooler per hour = 1080 gallons.

Total water used on three coolers = 3240 gallons per hour.

Water temp., in = 13° C.

In cooler bottom = 45° C.

Leaving bottom valve = 40° C.

Leaving lutes = 20° C. Cooled by atmosphere.

The water leaving the coolers contains 20 per cent. of dust by volume.

Water pressure on top sprays = 30 lbs. } Inside.

" " bottom " = 44 " }

Total gas passing plant = 2,800,000 cubic feet per hour.

" water used on dry coolers = 3200 gallons per hour.

" " " wet " = 3240 "

 6440

Total area of dry coolers = 16,560 square feet.

„ „ wet „ = 5,604 „

Total coolers 22,164 „

Total drop on gas from 280° C. to 80° C. = 200° C. drop under above conditions.

Final Cooler.

Height = 30 feet.

Diameter = 14 feet.

Volume = 4318.8 cubic feet.

Number of water jets = 26

Area of each jet = 0.75 square ins.

Total area of jets = 19.5 „

Water.

Gallons per hour used = 22,500

Temp. in = 13° C.

„ out = 24° C.

„ rise = 11° C.

Gas passing = 735,000 cubic feet per hour.

„ temp. in = 86° C.

„ „ out = 20° C.

„ „ drop = 66° C.

„ pressure at time = 5½ W.G.

Final Dryer.

Diameter = 8 feet.

Volume = 251 cubic feet.

Water taken out of gas = 60 gallons per hour.

After cooler { Dust contents at time = Nil.
Moisture contents at time = 17.6 grammes per cubic metre.
Water taken out by dryer = 1.34 „ „
= 7 to 10 per cent. of the total moisture after cooler and at 24° C.

TABLE I.

Test No.	N.	CO ₂ .	CO.	H.	B.T.U.'s.	Per Cubic Metre.		Chlorides as KCl. per Cent.	Carbonates as K ₂ CO ₃ per Cent.
						Dust. Grammes.	Moisture. Grammes.		
1	60.92	8.0	28.86	2.22	97.74	0.0014	8.15	35.34	1.77
2	60.22	8.0	29.4	2.38	99.9	0.0024	12.30	32.2	0.74
3	60.3	8.0	29.6	2.1	99.7	0.0014	9.4	31.0	2.98
4	61.6	8.0	28.3	2.1	95.63	0.0027	13.65	35.1	2.43
5	61.5	7.4	28.8	2.3	97.69	0.002	8.39	30.4	1.9
6	59.825	8.5	29.75	1.925	99.75	0.003	8.69	28.21	2.59
7	60.0	8.0	29.75	2.25	100.65	0.0012	9.75	31.76	1.17
8	59.87	8.0	29.33	2.80	100.81	0.0026	11.36	22.83	3.43
9	60.8	8.0	28.5	2.7	97.88	0.0024	12.42	25.97	2.35
10	63.07	6.75	27.75	2.43	94.76	0.0042	14.76	33.56	1.9

TABLE II.

$6 \times$ coke consumption per hour in lbs.

Weight of 1 cubic foot of gas = gas produced in cubic feet per hour.

The weight of 1 cubic foot of gas is calculated from its analysis and the specific weight of its constituents, as follows :

Analysis by Weight.		Specific Weight.		Taking Air as 1.
CO ₂	10·11	×	1·529	= 15·45
CO	30·85	×	0·960	= 29·60
H	0·08	×	0·067	= 0·0055
N	58·96	×	0·971	= 57·2
	<u>100·00</u>			<u>102·2555</u>

$$\therefore \frac{100 \cdot 2555}{100} = 1 \cdot 03 \text{ specific weight of gas comparing with air as 1.}$$

$$\text{Weight of 1 cubic foot of air} = \frac{40}{T}. \quad T = \text{absolute temperature.}$$

$$\frac{40}{461+32} = \frac{40}{493} = 0 \cdot 0811 \text{ lbs.}$$

Hence weight of 1 cubic foot of gas = $0 \cdot 0811 \times 1 \cdot 03 = 0 \cdot 0835$ lbs.

Therefore gas produced =

$$\frac{6 \times 20 \cdot 5 \times 2240}{0 \cdot 0835} = 3 \cdot 3 \text{ million cubic feet per hour.}$$

In conclusion, I am indebted to Messrs. Palmer's Ship-building and Iron Company for permission to read this paper.

DISCUSSION.

Mr. A. LENNOX LEIGH (Frodingham) said one of the objections to the type of gas cleaner described was the initial capital cost and, to some extent, the cost of running it, because of the expense of the renewal of cleaning bags. He was very hopeful that in the future both those difficulties could to a great extent be met. With cotton cleaning bags the temperature could not be raised above a certain amount; the makers said about 100° C., but perhaps slightly higher. If a higher temperature than that were used, the cotton fabric perished and the bags did not last as long as they should do. Some experiments had been made with a fabric of asbestos. He could not say that it had, so far, been tried out properly and could give no particulars, but if an asbestos bag could be made to replace the cotton bag it would at once do away with objection. If the gas was required for stoves and boilers, it could be drawn through the asbestos bag and the initial temperature retained. It was only a question of interest at the moment, but it looked very promising. It was apparently quite possible to weave asbestos material in the same way as cotton material to any form required. For those who did not want the gas to be so clean but were satisfied with 0·1 to 0·8 gramme per cubic metre, it was only a question of using a bag with a less close texture, while anyone who required gas thoroughly cleaned for gas-engine purposes could have a bag of closer texture and get cleaner gas. In the latter case more power would have to be used. It added very much to the flexibility of the apparatus if a bag could be made to any texture required, and thus enable very clean or moderately clean gas to be obtained.

Mr. A. HUTCHINSON, Member of Council, said he was interested to hear what Mr. Leigh had said with regard to the substitution of asbestos for cotton, as that would remove one of the great disabilities in the Halberg-Beth process. He did not think the author's statement was quite fair, that the cost of running or the power consumption in an electrostatic plant was high. The power consumption was exceptionally low, and when considering the question, the principal reason why he (Mr. Hutchinson) had adopted the electrostatic method was that the capital cost was very much lower compared with the cost of other processes.

Mr. H. M. RIDGE (London) said that the question of gas cooling by the Halberg-Beth process, when hot gas had to be cleaned, was the biggest difficulty in actually working the plants at the present time, and the electrostatic method possessed advantages in that

connection. It was noteworthy that in works like Esch, in Luxemburg, it had been found preferable to use the Halberg-Beth gas-cleaning system, and not the electrostatic or the wet method, in spite of the fact that cool, moisture-laden gas had to be treated, so that in cold weather water collected in the dirty gas mains. In other words, no cooling was required. It might have been assumed that where there was cold gas saturated with moisture, the addition of water in wet cleaning would not matter, or alternatively that in such cases the electrostatic method could be used. It had to be borne in mind that in various plants in Luxemburg and Lorraine it was necessary, for the Halberg-Beth plants, not to cool the gas before it went to the plant, but on the contrary to heat it, and a considerable amount of heat was required in many cases. In one of the works which he had visited early last year, the temperature of the gas had to be raised by some 50° to 55° C., and a good deal of coal was burnt for that purpose, which was all the more important owing to the grave shortage which prevailed then. He could not quite agree with the author with regard to boiler firing, because where gas was burnt in stoves or boilers, it should be put in at a high temperature. The generation of cheap power in the country was most important. The result of the adoption of modern gas-cleaning methods by the whole of the blast-furnace works in Great Britain would be a very large surplus of gas; this was at present not available, owing to the higher consumption in the stoves and boilers when burning dirty gas. The surplus which would be freed could be efficiently used for the generation of electric power and its supply to the surrounding country. This point not only affected the ironmasters financially, but was also of supreme national importance. He would like to mention in that connection the position at Hagondange, in Lorraine, where there were, in addition to the blast-furnaces, steelworks and complete rolling-mills. The blast-furnace gas was properly cleaned, and after supplying the power for the blowing-engines, furnace hoists, rolling-mills, &c., as well as the whole of the gas for the open-hearth steel furnaces, there was still a considerable surplus of gas available for generating electric current for lighting the neighbouring villages and supplying power for sale to other adjoining works. This was highly important, because that power was generated at extraordinarily low cost. He would like to raise what he ventured to suggest was a very important question. A few months previously Mr. Hutchinson had read a very interesting paper on electrostatic cleaning of blast-furnace gas at the Cardiff meeting of the Institute, and at the present meeting there was the paper of Mr. Fowles. Personally, he looked upon the subject as being of such very great interest and importance, not only scientific but commercial, to the whole of the iron and steel industry as well as to the other industries of the country, that he thought it would be a good thing to arrange for a symposium for a complete discussion on the question of gas cleaning, at which the whole of the various methods would be discussed and

compared and data gone into thoroughly. Regarding the Halberg-Beth method, the results on the Continent and in Great Britain had proved its efficiency. Mr. Hutchinson in his interesting paper gave what he said were preliminary figures, and he would like to ask for further information, and especially whether the figures Mr. Hutchinson then gave as to the dust content of the gas after treatment had remained approximately constant or had been improved, or the reverse. That question was important for the comparison of the processes, and of great interest to the various blast-furnace works that had not yet installed modern gas-cleaning plant, but would be forced by circumstances to do so. He would be very grateful if Mr. Hutchinson could give any information on that subject.

Mr. F. W. HARBORD, Member of Council, said that no doubt everyone looked forward to the time when gas-engines would be used as the motive power in all blast-furnace plants, and in that direction lay great economy, but there would be for a number of years works which could not instal gas-engines, as they could not afford to scrap their existing engines, and did not, therefore, require to clean the gas to the extent necessary for a gas-engine. What was badly needed was a method of dealing with the gases which would remove sufficient dust to enable such gases to be used in hot-blast stoves and under boilers, with greater efficiency and also effect saving in the cost of refractories. At present the bar to those installations, whether electrostatic or Halberg-Beth, was the cost. The Kling Weidlin dry method of gas cleaning, which had been recently introduced in the United States, and was now being installed at one or two works in Great Britain, depended upon the removal of the dust by filtration through an iron wool-mattress and was giving very promising results, but it did not profess to clean down to the extent required for gas-engines. It was less costly than the other methods, but still very costly for the work it had to do. He was inclined to think that a great deal might be done with cyclone systems. The old cyclone had been tried again and again, but he did not think it had been systematically thrashed out in the scientific way in which it ought to have been. He had recently received information respecting the use of specially designed cyclones in connection with other metallurgical works where it had been a great success in dealing with dust which was very much lighter and finer than that which they had to deal with from blast-furnaces, and the cost of the apparatus was a few hundred pounds compared with thousands of pounds for the other methods. He thought insufficient attention had been given by engineers to the design of a cheap form of apparatus for dealing with the gases required for combustion purposes alone.

Mr. G. W. HEWSON (Jarrow-on-Tyne) said he was pleased that Mr. Ridge had suggested a symposium on the question of gas cleaning.

As Mr. Ridge had already pointed out, the Germans had proved conclusively the utility of cleaning the gas. Terms had, of course, to be used in their relative senses. For instance, when he spoke of clean gas he meant, in the present case, gas clean enough for gas-engine purposes, which was specified as being under 0.005 gramme per cubic metre. The question of cooling the gas and of cleaning it resolved itself into how the gas was going to be used after it had been cleaned. To use the gas directly in gas-engines was the ultimate economy. Only 28 to 30 per cent. of the cleaned gas was required for stove purposes; roughly 70 per cent. of the gas was available for engine purposes. If it were necessary, then, to clean 70 per cent. of the gas and to cool it, the whole lot might as well be cleaned. There was one advantage in cleaning the whole of the gas, namely, that it was possible to draw, say, 75 per cent. of the gas for the engines when the stoves did not require so much, and give more back to the stoves when they did require it. His firm had found—and he believed it would be confirmed by others—that cold dry gas gave a higher calorific intensity either in boilers or in stoves than hot wet gas. The paper indicated that in the old days it had been necessary to use 200 tons of coal in the boilers not only to raise steam, but in order to get the gas to ignite or to keep alight. In the present day, without any coal whatever, the gas very readily burned, and gave a higher initial temperature than could be obtained with the old system. The dust recovered from the gas was the finer dust which was richest in potash content, and he thought it would be found eventually, though perhaps not at present, that it would pay to clean the gas for the recovery of potash alone. During the last three years, without cleaning the whole of the gas—because at first they started with one plant and now had three—his firm had collected about 7500 tons of dust, equal to a content of 1500 tons of potassium chloride. Latterly they had been recovering at the rate of about 25 tons of potassium chloride per week from a three-furnace plant. That, multiplied throughout the country, would give an enormous quantity of potash recoverable. The amount and richness of the dust recovered, however, in a cleaning plant, depended largely on the elimination of the heavier dust soon after it left the blast-furnace and, as Mr. Fowles had indicated in his paper, it was a question of reducing, if possible, the velocity of the gas in order that the heavier particles might be deposited before they reached the cleaning plant, so that the plant only had to deal with the finer particles. In some places he believed economisers had been utilised for cleaning the gas, but blast-furnace dust, generally speaking, was deliquescent. He believed the dust at Skinningrove, for example, was much more deliquescent than the dust at Jarrow. If, therefore, the gas were cleaned rapidly by economisers, by having a large surface some portion of the gas dropped its moisture, and that moisture collected the dust and clogged the tubes. With larger surfaces that danger was eliminated, so that the large diameter coolers were much better in operation than economisers.

Mr. L. ROTHERA (St. Albans) wished to make a few remarks from the electrical point of view as to how to make use of the gas when it was cleaned. He thought it was a well-accepted fact that the only way of really making a power balance as compared with the amount of gas available in a steelworks was by making use of the full quantity of gas in the most efficient way. Mr. Fowles gave the power available from the gas when used in gas-engines as 6500 horse-power, whilst if burnt under boilers only 1200 horse-power was available. That difference showed a more favourable result for the gas-engine than could be expected in practice under modern conditions, and it was now agreed that, if gas-engines were used, something between two or three times the quantity of power could be generated as compared with that obtained if the gas were burned under boilers and the steam utilised in turbines. The main arguments hitherto used against gas-engine generation of power had been the heavy capital cost, the upkeep charges, and the difficulties attendant on successful parallel running. Taking those points in order, it had to be admitted that the capital costs of the slow speed gas-engine were very heavy, but that cost had been considerably reduced by the introduction of the high-speed vertical engine, which was giving satisfactory results. The cost of upkeep on the slow-speed horizontal engine, given good conditions of gas cleaning (a vital condition) and satisfactory attention, should be very low, and probably somewhat less than in the case of the vertical high-speed engine, although that point had not yet been fully tested out. The objection regarding parallel running had now ceased to exist, for, with correct design of engines, flywheels, and generators, no difficulties would occur in the running of any number of sets or in paralleling them with an external source of supply driven, say, by steam turbines. Taking into account the demand for cheap electrical power in the country, it would appear that the method of utilising existing quantities of gas to produce more than twice the power was one which, in the future, would be, of necessity, adopted, and it would be considered quite the wrong thing to make use of gas for burning under boilers when gas-engines were available.

Mr. G. B. GARRETT (London) said Mr. Fowles had given a very interesting and instructive paper on what was probably at the present time the most successful dry cleaner for cleaning gas to the degree necessary for use with gas-engines. It was his own opinion, however, that with that system rather needless expense was incurred in cleaning the gas to such a fine degree for use in hot-blast stoves and under boilers, if boilers were used; in other words, that it was preferable to instal a cleaning system to rough clean all the gas from the furnaces and by-pass to some such system as a Halberg-Beth only that amount of gas which was destined for use in the gas-engines. He believed that an arrangement similar to that was now being planned by the Appleby Iron Company, whereby they rough-cleaned all their gas,

and in connection with that rough-cleaner had a final cleaner which handled only the gas destined for the engines. By combining two such systems, a cool clean gas was obtained for the engines and a hot clean gas for the stoves, the gas for each of those auxiliaries being cleaned only to the degree necessary to ensure their most efficient working. It would be most interesting if Mr. Fowles could give some present-day figures regarding the capital cost of the Halberg-Beth plant to deal with the output of gas mentioned in the paper, and it would then be possible to arrive at a more correct financial comparison of his method with the one which he (the speaker) suggested. While Mr. Fowles was emphatic in his declaration that the day of the gas-fired boiler and steam-driven equipment was over, he (Mr. Garrett) could not help feeling that he was a little extreme in his disparagement of that equipment. The latest developments in America in gas-fired boilers tended to show that with large up-to-date boilers clean hot gas, clean water and preheated air for combustion, a boiler efficiency of 80 per cent. and over could be obtained. In conversation with the blast-furnace superintendent from one of the plants where they were cleaning their gas by the dry clean process, he had been informed that they were able to get 150 to 200 per cent. rating out of their existing boilers by the use of blast-furnace gas alone. The chief engineer of the Ohio Works of the Carnegie Steel Company in a recent report advocated the installation of steam-driven plant producing steam at 300 to 350 lb. pressure and about 200° superheat, running that steam through high pressure turbines, which would exhaust it at about 180 lb. at 100° superheat, for its ultimate use in steam-engines and turbines. That gentleman's arguments in support of that contention warranted a very close investigation as to whether gas-engines, although highly economical thermally, were as economical financially as would appear at first sight.

CORRESPONDENCE.

Mr. J. A. C. EDMISTON (Hamilton) wrote that it was a very wasteful policy to generate energy by firing boilers with gas, when considering the specific heat, calorific intensity, and sensible heat of the products of combustion. That point was, in many cases, overlooked by some of our chemists and engineers.

He (Mr. Edmiston) would like the author to explain more lucidly his method on Table II. for determining the volume of gas.

Mr. S. H. FOWLES, in replying to the discussion, remarked that several speakers had made observations, based apparently on actual experience, which were therefore so much the more valuable. Mr. Lennox Leigh raised the point of capital cost, which was purely a

condition due to the war. The total cost of filter bags and renewals was 1d. per million cubic feet of gas cleaned down to 0.0005 gramme per cubic metre. With temperatures of 100° C. the bags lasted from 1½ to 2 years, which was quite a good life. It was very doubtful if an asbestos filter bag would be of any service, because it would at once add weight to the lifting mechanism and so increase wear and tear. The fabric was not so tough as cotton and would be more susceptible to moisture deposit, which would give some trouble. The paper showed that, if a plant were worked under the conditions set out, the costs of labour, bag-changing, upkeep, &c., would be reduced to a minimum, and the minimum weights would be imposed on the shaking gear.

Both Mr. Leigh and Mr. H. M. Ridge seemed very anxious to retain the sensible heat in the cleaned gas. If the gas were dry, then that would certainly be a great advantage, but with gas at 25 to 35 per cent. saturated, as most blast-furnace gases were in this country, and leaving the furnace, say, at 300° C., then if the moisture were retained and the gas passed through the stoves or boilers with flue gases, leaving at 400° C., then 7½ per cent. of the total heat would be lost. If, on the other hand, the gas were cooled down and raised to 100° C., and dried so that it was, say, only 8 per cent. saturated, there would then be a total heat loss of 5 per cent.; therefore the Halberg-Beth process had a heat-retaining capacity of 2½ per cent. over the other types of cleaners.

The question of running costs was raised by Mr. A. Hutchinson. Although it was true that the electrostatic plant consumed less power as a unit, yet in making a comparison the degree of cleanliness of the gas must be stated. The electrostatic consumed 50 kw.h. plus 15 horsepower for conveyers to clean 3 million cubic feet from 5 to 6 grammes down to 1 gramme per cubic metre, the gas being at 250° C., whereas the Halberg-Beth consumed 150 kw.h. in cleaning 4 million cubic feet from 5 to 6 grammes down to 0.0005 gramme per cubic metre, the gas being at 100° C. It would be seen the gas quantities were very different, as were the temperatures and the cleanliness. The respective figures were 20 kw.h. and 37.5 kw.h. per million cubic feet. It was very doubtful whether the electrostatic could get down to 0.0005 gramme per cubic metre for 37.5 kw.h. per million cubic feet even if the plant were duplicated for the purpose.

Some very good information on the subject was given by Mr. Ridge. He (Mr. Fowles) was in agreement with many of his points, and he would be most happy to assist in any way possible to add to the discussions on this most important subject.

Mr. F. W. Harbord referred to the partial cleaning of the gases. That would be determined by the amount one was prepared to expend on flue cleaning, furnace stopping, and loss of potash in the finer dust. Regarding costs, an up-to-date plant such as described with a completely new gas-engine plant should repay itself in four years. The

question of a plant of cheaper design was still occupying the minds of engineers, but it would have to be a plant where the back pressures on the furnace burden must be capable of regulation at will, in accordance with furnace requirements. So far that had only been achieved by the Halberg-Beth plant, and it was certainly a great advantage to the furnace working.

Mr. J. A. C. Edmiston's remarks were very gratifying, referring as they did to several points of great importance. In explanation of Table II., 6 cubic feet of gas are formed per lb. of coke used, so that

$$\frac{\text{coke in lbs. used per hour}}{6 \times \text{weight of 1 cubic foot of gas}} = \text{quantity made.}$$

Mr. G. W. Hewson had added some very useful information, and appeared convinced of the usefulness of the plant when worked on up-to-date principles. It must be borne in mind that the method of working the plant was very different from the German method, and that alone removed many of what were previously obstacles.

In summarising the discussion the main points raised were:

(1) Retention of sensible heat.

(2) The cleaning was taken too far for general purposes.

In considering the conditions likely to prevail, say, ten years hence, and judging by the necessity for economy in order to retain our position in the world's markets, there was no doubt that every particle of our fuel and by-products would have to be used to their maximum efficiency. A much higher stove efficiency would therefore have to be maintained, and more gas must be made available for the generation of energy outside the ironworks.

The maximum amount of potash must be collected, the losses by the various methods of cleaning must be taken very carefully into account, and the final balance-sheet would prove which was the best method of cleaning.



Iron and Steel Institute.

BLAST-FURNACE AND CUPOLA SLAGS.

THEIR COMPOSITION AND GRAPHIC METHODS FOR DETERMINING THEIR CONSTITUTION.

By J. E. FLETCHER (DUDLEY).

SLAGS are now generally recognised as being more or less complete solutions of acid and basic oxides, their oxygen contents—depen-

THE GENESIS OF ORE GANGUES AND FUEL ASH

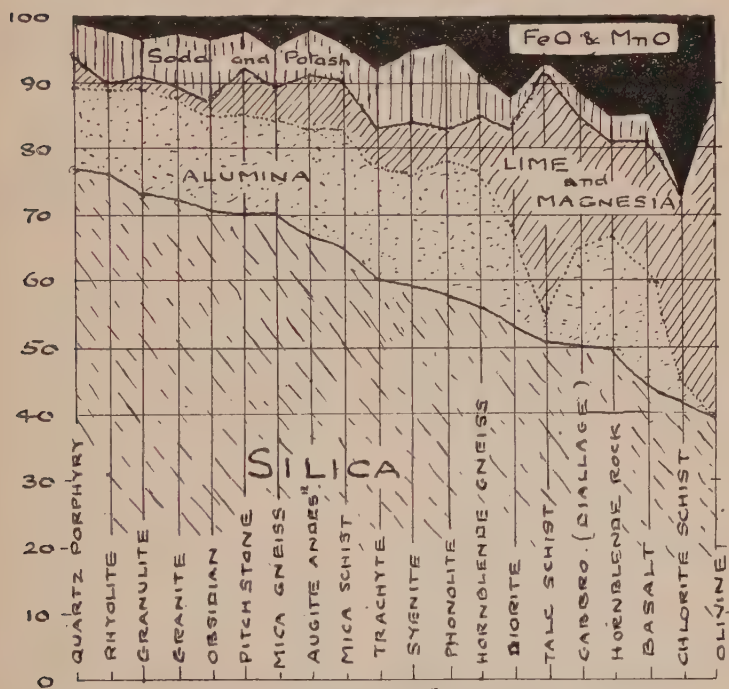


FIG. 1.—Analyses of Igneous Rocks.

dent upon the union of that gas with the metals or metalloids present—determining the acid, basic, or neutral character of the slags.

BLAST-FURNACE SLAGS.

In blast-furnace practice the natural gangues of an ore are usually most heterogeneous and varied in character. Percolations of gases and of liquid material may have filled in the interstices of the porous portions of the ore mass, whilst in other areas the primary homogeneous character of the ore persists longer (Fig. 1). When an ore is reduced the melted gangues are far from uniform in composition and may contain free and unfused refractory oxides. Hence the difference in the character of the streams of slags as they flow through the lower portions of the blast-furnace column, and the lack of homogeneity of the commingled slags when they first reach the hearth. The problem of smelting ores of similar general analysis but of vastly differing physical composition is bound up with the variation in the viscosities of the slags descending through the hearth or lower portion of the boshes.

As illustrating this point the gangue slag analyses of four of the ores cited by Mr. Clements in his recent paper on "Blast-Furnace Practice"¹ are of interest. The lime and silica contents of the ores taken represent four distinct types:

(1) High SiO ₂ .	SiO ₂ .	13.38	per cent. in ore	38.0	per cent. in gangue slag		
	Al ₂ O ₃ .	7.60	" "	21.5	" "	" "	" "
	MnO .	0.00	" "	00.0	" "	" "	" "
	CaO .	14.05	" "	39.8	" "	" "	" "
	MgO .	0.28	" "	0.7	" "	" "	" "
(2) Low SiO ₂ .	SiO ₂ .	3.70	" "	10.4	" "	" "	" "
	Al ₂ O ₃ .	6.10	" "	17.2	" "	" "	" "
	MnO .	1.80	" "	2.7	" "	" "	" "
	CaO .	23.00	" "	67.5	" "	" "	" "
	MgO .	0.90	" "	2.2	" "	" "	" "
(3) High CaO.	SiO ₂ .	5.37	" "	14.2	" "	" "	" "
	Al ₂ O ₃ .	8.10	" "	21.5	" "	" "	" "
	MnO .	1.00	" "	2.6	" "	" "	" "
	CaO .	22.50	" "	59.9	" "	" "	" "
	MgO .	1.00	" "	2.6	" "	" "	" "
(4) Low CaO.	SiO ₂ .	9.30	" "	31.1	" "	" "	" "
	Al ₂ O ₃ .	8.10	" "	27.0	" "	" "	" "
	MnO .	1.14	" "	2.7	" "	" "	" "
	CaO .	11.00	" "	38.0	" "	" "	" "
	MgO .	0.37	" "	1.2	" "	" "	" "

¹ F. Clements, "British Blast-Furnace Practice," *Journal of the Iron and Steel Institute*, 1920, No. I.

It has been suggested by Hilgenstock and others, including Mr. H. E. Wright in his paper on "Chemical and Thermal Conditions in Blast-Furnace Practice,"¹ that blast-furnace slags consist of a solvent silicate in which the remaining constituents are dissolved. The author's investigations distinctly support this view, and the present paper is an attempt to draw, from information collected during the past ten years in a wide field, such conclusions as appear to simplify the generally complex slag problem.

The solvent silicate referred to appears to be of the ortho-silicate $2\text{RO} \cdot \text{SiO}_2$ type, in which are dissolved the excess SiO_2 , Al_2O_3 , and the remaining sulphides and acid oxides.

The calcic silicate $2\text{CaO} \cdot \text{SiO}_2$ having the ratio $\text{CaO}/\text{SiO}_2 = 65/35$ per cent. and the magnesia silicate $2\text{MgO} \cdot \text{SiO}_2$, with ratio $\text{MgO}/\text{SiO}_2 = 57/43$ per cent., may be safely considered as the basal solvents in blast-furnace slags. They are present together in varying proportions. Table I. is useful as indicating the analyses resulting from varying ratios of $2\text{RO}/\text{SiO}_2$ in a range of mixtures of the two constituents CaO and MgO .

TABLE I.

Ratio CaO MgO.	CaO per Cent.	MgO per Cent.	SiO_2 per Cent.	Ratio $\left\{ \begin{array}{l} \text{MgO} \\ \text{CaO} \end{array} \right\} : \text{SiO}_2$ Per Cent.
...	65.1	0.0	34.9	65.1 : 34.9
10.0	59.1	5.2	35.7	64.3 : 35.7
9.0	58.5	5.7	35.8	64.2 : 35.8
8.0	57.7	6.4	35.9	64.1 : 35.9
7.0	56.9	7.1	36.0	64.0 : 36.0
6.0	55.7	8.1	36.2	63.8 : 36.2
5.0	54.2	9.5	36.3	63.7 : 36.3
4.0	52.0	11.4	36.6	63.4 : 36.6
3.0	48.8	14.2	37.0	63.0 : 37.0
2.0	43.3	19.0	37.7	62.3 : 37.7
1.0	32.5	28.5	39.0	61.0 : 39.0
0.5	21.7	38.0	40.3	59.7 : 40.3
...	0.0	57.0	43.0	57.0 : 43.0

These silicates can be graphically illustrated by diagrams.

¹ *Journal of the Iron and Steel Institute*, 1920, No. I.

Fig. 2 depicts the ortho-silicates $2\text{CaO}.\text{SiO}_2$, $2\text{MgO}.\text{SiO}_2$, and a similar graph of the typical mixed silicates $2\text{RO}.\text{SiO}_2$.

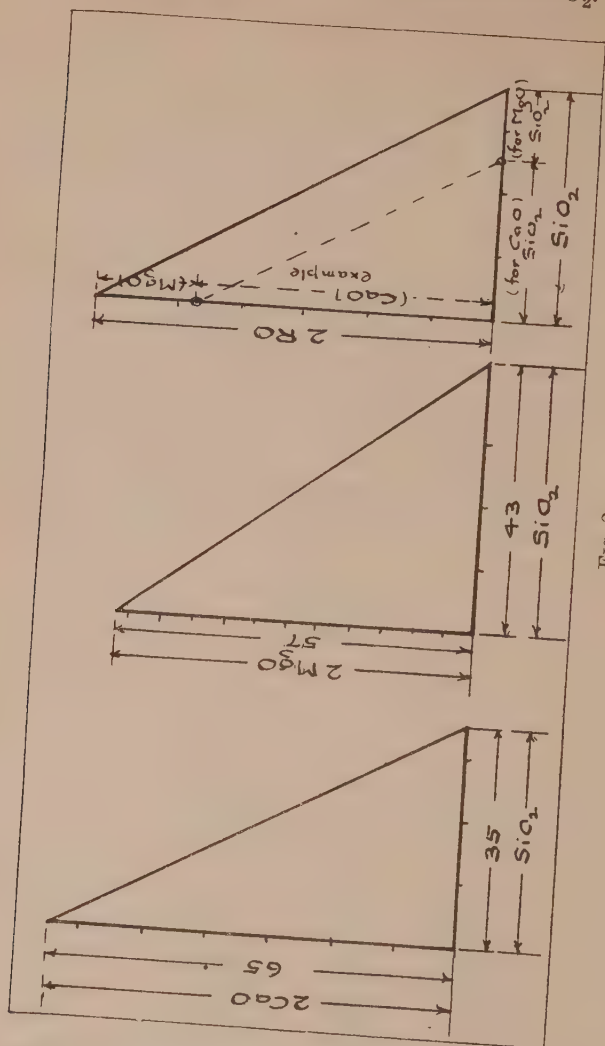


FIG. 2.

An examination of blast-furnace slag analyses will show that their composition can be represented diagrammatically, the RO silicates being plotted as ordinate and the SiO_2 and Al_2O_3 as abscissa (Fig. 7). The shaded area adjoining the portion of the horizontal is marked $(+\text{SiO}_2)$. This value is the per-

centage of SiO_2 remaining after taking sufficient SiO_2 to satisfy the ratio $2\text{RO}/\text{SiO}_2$.

If Al_2O_3 be a neutral constituent in blast-furnace slags, as it appears to be, the excess SiO_2 is the active acid solute from whence the siliconisation of the iron proceeds. This solute, along with the inactive Al_2O_3 , is dissolved in the inert or neutral ortho-silicate $2\text{RO}.\text{SiO}_2$.¹

An examination of a large number of typical slags from different blast-furnaces throughout the country, on the hypothesis that the solvent 2RO silicate contains the remaining SiO_2 and Al_2O_3 as solutes, has led to the following estimation of their composition :

Solvent silicate of $2\text{CaO}.\text{MgO}.\text{SiO}_2$ type	60 to 75 per cent.
Excess silica as solute	3 to 12 "
Alumina	10 to 28 "
CaS, FeO, MnO, TiO_2 , &c. . . .	4 to 10 "

Table II. gives details of six slags and their compositions based on the foregoing hypothesis:

TABLE II.

	SiO_2 .	Al_2O_3 .	CaO MgO .	MnO.	FeO.	CaS.	$\frac{\text{CaO}}{\text{MgO}}$.	$2\text{RO}.$ SiO_2 Solvent.	Free $\text{SiO}_2 +$ Solute.	Al_2O_3 Solute.
	%	%	%	%	%	%	%	%	%	%
Basic	34.0	14.5	44.0	1.5	2.0	4.0	37.0	73.9	8.6	14.5
Foundry	32.0	19.5	45.0	0.5	1.0	2.0	11.7	72.2	6.7	19.5
Forge	33.0	17.0	45.0	0.7	1.3	3.0	15.2	72.8	7.2	17.0
Foundry	30.3	16.2	44.8	2.0	2.0	4.7	18.0	75.7	3.4	16.2
Cleveland No. 3	30.5	25.7	41.5	1.2	1.2	2.1	3.5	68.9	5.5	25.7
Hæmatite 2 per cent. silicon	36.4	12.8	44.8	1.8	2.8	3.2	18.4	74.2	9.8	12.8

It has been correctly observed by a number of workers in slag research that under working conditions blast-furnace and other slags tend towards inertness or neutrality, and Table II. shows

¹ Possibly the alumina is present in a tricalcic aluminate $3\text{CaO}.\text{Al}_2\text{O}_3 +$ (or $3\text{RO}.\text{Al}_2\text{O}_3$) of neutral character. In such case the $2\text{RO}.\text{SiO}_2$ content would be diminished and the free silica increased. The main contention would remain unaltered, viz., that the slags are composed of free silica dissolved in a matrix of neutral or inert character possessing stability in the liquid state at or above a definite temperature. Research on the melting points, &c., of a series of synthetically prepared slags of composition $(2\text{CaO}.\text{SiO}_2 + n3\text{CaO}.\text{Al}_2\text{O}_3 + n_1\text{SiO}_2)$ would be of practical utility.

inferentially that alumina, apart from its functions in lowering the fusion temperatures and affecting the viscosity of the silicate in which it is dissolved, is inactive. If it (alumina) does tend to make the slag dissolve CaS more readily it is probable that this is owing to the greater liquidity given. The silica present in excess of the requirements of the $2\text{RO}.\text{SiO}_2$ constituent falls as the iron becomes alloyed with the silicon reduced from the slag.

The author has shown elsewhere¹ that during the siliconising of the iron in the hearth the SiO_2 content of the slag diminishes. Hence for similar burdens the slags resulting from the production of 1, 2, 3, or 4 per cent. silicon irons will be progressively poorer in silica content.

This point is brought out in Table III., wherein five kinds of ores (and flue cinder) are investigated. It is seen that the greater

TABLE III.

Class of Ores, &c., used.	Slag per 100 lbs. Pig Iron. Lbs.	Silicon in Pig Iron. Per Cent.	Slag Analysis. CaS, &c., taken at 4 per cent.			SiO_2 Activity. Free SiO_2 . Per Cent.
			SiO_2 . Per Cent.	$\text{CaO}.\text{MgO}$ (RO). Per Cent.	Al_2O_3 . Per Cent.	
Cleveland Fe = 28 per cent.	122.6	0.0	33.1	37.0	25.0	10.6 ²
	120.5	1.0	31.8	38.1	26.1	9.3
	118.3	2.0	30.6	39.1	26.3	7.6
	116.5	3.0	29.5	40.0	26.5	5.6
Northampton Fe = 32.5 per cent.	140.1	0.0	36.5	42.1	17.4	11.7 ²
	138.0	1.0	35.3	43.0	17.7	10.1
	135.8	2.0	34.5	43.5	18.0	9.0
	133.7	3.0	33.3	44.5	18.2	7.2
South Lincs. Limey Fe = 25.2 per cent.	157.9	0.0	33.5	38.0	24.5	10.9 ²
	156.8	1.0	33.0	38.0	25.0	10.5
	153.6	2.0	32.2	38.5	25.3	9.5
	151.4	3.0	31.2	39.2	25.6	8.2
Hæmatite Fe = 60.8 per cent.	49.5	0.0	38.5	42.8	14.7	13.2 ²
	48.9	1.0	35.7	44.9	15.4	9.2
	45.2	2.0	32.6	47.2	16.2	4.9
	43.2	3.0	29.5	49.3	17.2	0.8
Flue cinder Fe = 50 per cent.	161.4	0.0	42.6	47.4	6.0	15.4 ²
	159.3	1.0	42.1	47.8	6.1	14.3
	115.7	2.0	41.1	48.7	6.15	12.8
	155.0	3.0	40.5	49.3	6.20	11.8

¹ Paper "On the Function of Slags in Blast-Furnace Operation," Staffordshire Iron and Steel Institute, 1916.

² Primary slags.

the slag yield per ton of iron made the smaller the range of SiO_2 activity for each per cent. of silicon in the pig iron.

The effect of temperature in determining the range of silica activity and of the resulting alloying actions is illustrated in

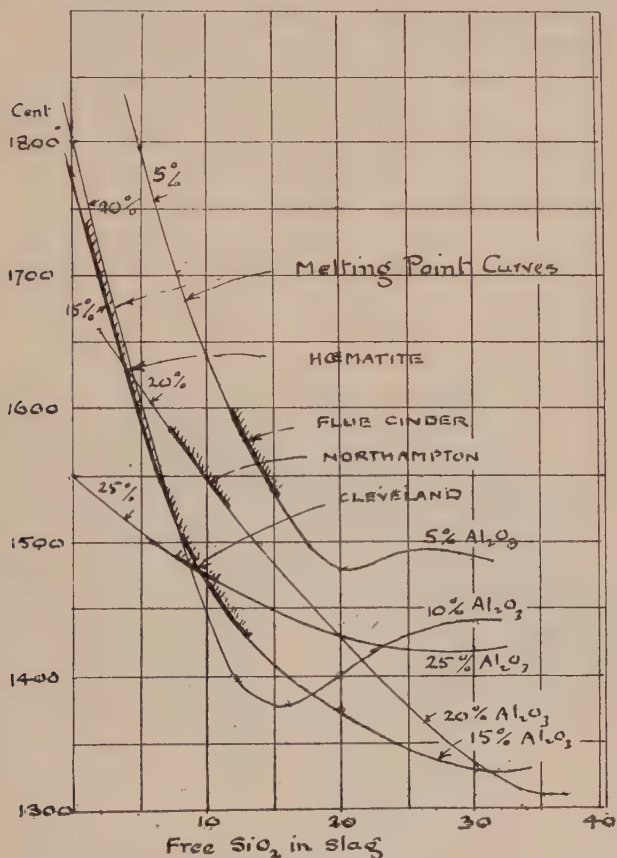


FIG. 3.

Fig. 3, which records the melting point temperature curves of the examples cited in Table III. The curves are thick lined in the portions involved in the making of 3 per cent. silicon irons. The lower temperatures of the thick-lined portions of the curves are the melting points of the primary slags, the higher those of the fusion points of the working slags when iron of 3 per cent. silicon content is being made.

It should be noted that the primary slag of the hæmatite example melts at below 1430°C ., and that considerable super-heating beyond this temperature is necessary if silicon is to be reduced from the slag. The need for adding aluminous ores to the burden in such cases, in order to lower the fusion point of the slag and to keep it sufficiently fluid, is evident.

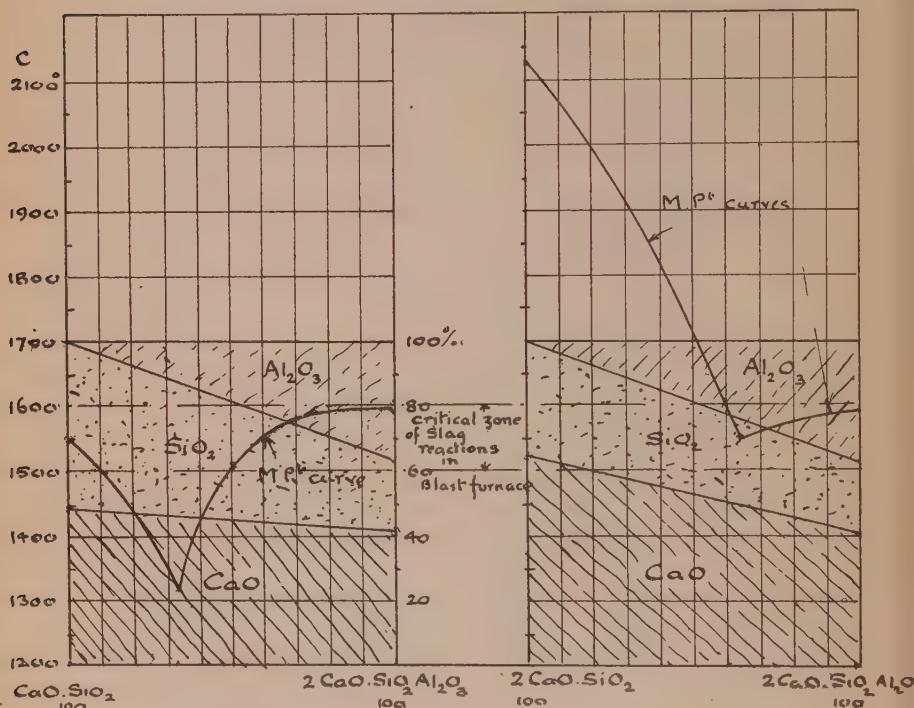


FIG. 4.

In arriving at the above conclusions the work of Rankin and Wright and others in the researches on slags in connection with the American Geophysical Society has been invaluable. The facts recorded in these researches are of the utmost importance and, although the systems of slags occurring in blast-furnace practice are combinations of the silicates ($2\text{CaO.SiO}_2 + 2\text{CaO.Al}_2\text{O}_3.\text{SiO}_2$) and ($\text{CaO.SiO}_2 + 2\text{CaO.Al}_2\text{O}_3.\text{SiO}_2$), Fig. 4, the working slags may be safely and practically considered as solutions of Al_2O_3 and excess SiO_2 in the 2CaO.SiO_2 solvent.

It has been shown in the above researches that the meta-silicates $\text{CaO} \cdot \text{SiO}_2$ and $\text{MgO} \cdot \text{SiO}_2$, when superheated well above their melting points, become ortho-silicate in character, dissolving the excess SiO_2 . Similarly $\text{FeO} \cdot \text{SiO}_2$ becomes $2\text{FeO} \cdot \text{SiO}_2 + \text{SiO}_2$ on superheating. There is further evidence that in presence of

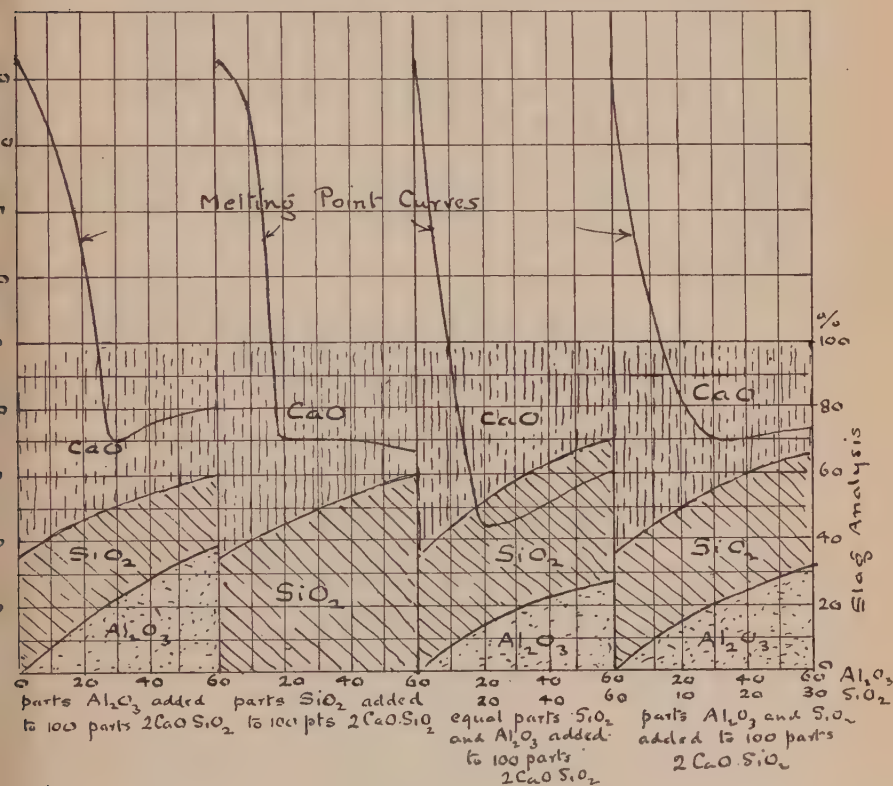


FIG. 5.

Al_2O_3 and Fe_2O_3 the amount of superheat needed beyond the melting points of the meta-silicates to bring about the change to ortho-silicate condition is reduced. This is shown in Fig. 5, where the influence of Al_2O_3 and SiO_2 additions to the ortho-silicate $2\text{CaO} \cdot \text{SiO}_2$ in reducing the melting point temperatures is seen.

Moreover, though it is not yet possible to prove that calcic

sulphide (CaS) is dissolved in the 2RO silicate, there is a good deal of evidence to show that this sulphide dissolves most readily in a slag of $2\text{RO}.\text{SiO}_2 + n\text{Al}_2\text{O}_3$ type, which is most fluid when the alumina content exceeds 20 per cent. Feild's researches on the viscosity of blast-furnace slags clearly revealed the fact that in a series of slags whose alumina contents varied between 10 to 35 per cent., with SiO_2 per cent. ranging from 18 to 43, the most liquid slag at tuyere zone temperatures (about $1550^\circ\text{C}.$) was one whose SiO_2 activity was nil and whose alumina content was about 35 per cent. See Fig. 6 (a).

The thinning effect of alumina on the $\text{SiO}_2.\text{Al}_2\text{O}_3$ mixtures in refractories manufacture is now well recognised, as is also the viscosity-increasing effect of SiO_2 , especially where this is present in the free state.

In Fig. 6 the graphs of three representative slags are given with the corresponding liquidity (the reciprocal of viscosity) curves alongside. They are strikingly illustrative of the influence of free or excess silica and alumina in $(2\text{RO}.\text{SiO}_2 + x\text{SiO}_2 + n\text{Al}_2\text{O}_3)$ slags.

The practical value of the slag graph is further seen in determining the CaO additions to blast-furnace burdens.

The probable coke consumption being assumed, the weight of SiO_2 , Al_2O_3 , CaO , and MgO in the burden and coke ash is determined say per 100 lbs. of pig iron produced. Half the MnO present may be considered practically as equivalent to the CaO . The calcium required to form CaS may be taken as CaO and equal to 1.75 times the weight of the sulphur in the ores and coke.

In Fig. 7 the alumina and silica are plotted along the line AC , the $\text{CaO}.\text{MgO}$ and MnO along the ordinate AD . From a number of investigations the SiO_2 activity per cent. in the primary slag before silicon reduction has been found to be 32 per cent. of the total SiO_2 present in the slag. Hence Bx is taken as 0.32 AB and the line xE drawn, meeting the vertical at E . The inclination of this line is fixed by the expected CaO/MgO ratio in the slag (for purely CaO slags the ratio $\frac{\text{AE}}{\text{Ax}}$ is $\frac{65}{35}$, and for other $\text{CaO}.\text{MgO}$ slags the ratio is as given in Table I.). The length ED gives to scale the additional CaO required.

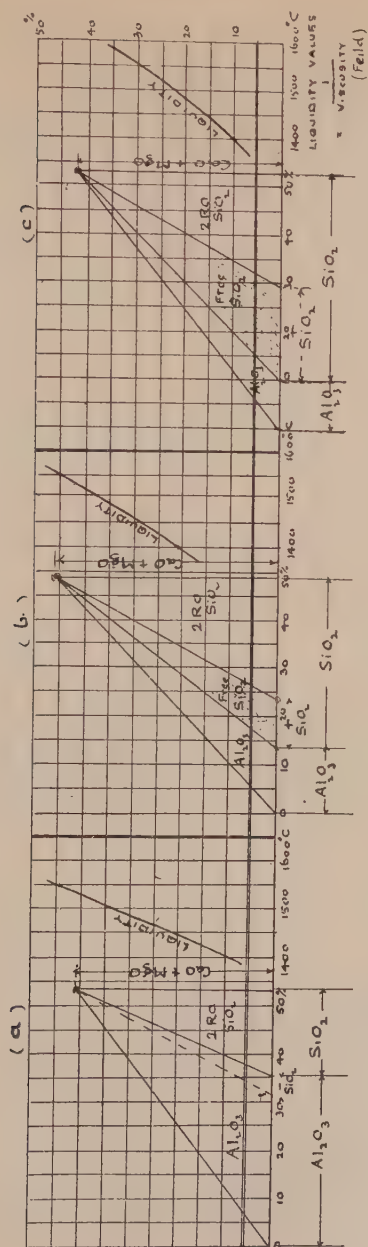


FIG. 6.

It appears to the author that the composition of the primary slag is of fundamental importance. If from the available data this composition be estimated and the primary SiO_2 activity of the slag known, thermal manipulations can be followed with a clearer conception of what is actually going on in the hearth of the furnace.

Of course the same graphic method can be used when

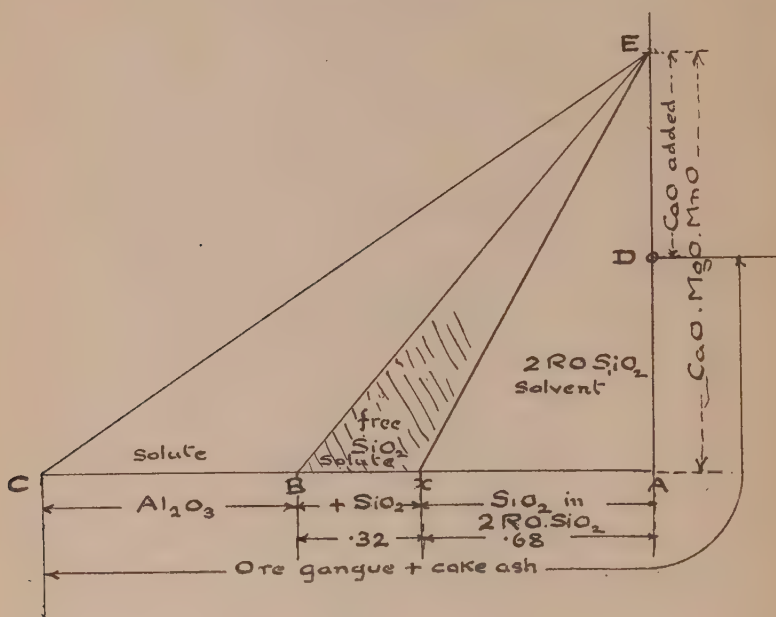


FIG. 7.

taking the desired analysis of the running slags as the basis for CaO additions, in which case the SiO_2 required for the silicon reduction must be added to the SiO_2 content in the running slag. By this means the analysis of the primary slag can be forecast.

If the SiO_2 activity in the primary slag be correct and the primary slag analysis indicates a slag of low melting point and viscosity, the character of the thermal additions necessary to give the desired silicon content in the pig iron can be foreseen.

INFLUENCE OF Al_2O_3 ON THE SiO_2 ACTIVITY IN
BLAST-FURNACE SLAGS.

It has been considered by several well-known furnace experts correct so to control the working slag composition that the $\frac{\text{CaO.MgO}}{\text{SiO}_2}$ ratio is a constant, the ratio $\frac{48}{93}$ being not infrequently adopted. This corresponds with a primary slag of about 12 per cent. SiO_2 activity when making basic iron.

Table IV. reveals the fact that as the alumina content of the slag increases (the ratio $\frac{\text{CaO}}{\text{SiO}_2}$ remaining constant) the silica activity decreases. In column B the variations in the constituents is estimated in the cases where the SiO_2 activity value remains constant.

TABLE IV.

Al_2O_3 per Cent.	SiO_2 per Cent.	CaO per Cent.	Free SiO_2 per Cent.	Al_2O_3 per Cent.	SiO_2 per Cent.	CaO per Cent.	Free SiO_2 per Cent.
0.0	44.2	55.8	14.2	0.0	42.5	57.5	11.3
5.0	42.0	53.0	13.3	5.0	41.5	53.1	11.3
10.0	39.8	50.2	12.6	10.0	39.0	51.0	11.3
15.0	37.5	47.5	11.9	15.0	37.0	48.0	11.3
20.0	35.3	44.7	11.2	20.0	35.4	44.6	11.3
25.0	33.1	41.9	10.6	25.0	34.6	41.4	11.3
30.0	31.0	39.0	10.0	30.0	31.9	38.1	11.3
35.0	28.7	36.3	9.1	35.0	30.0	35.0	11.3

A.

B.

In Fig. 8 these results are shown graphically, the melting point curves being added. A slag of eutectic character is given by Rankin and Wright as of composition :

Al_2O_3 per Cent.	SiO_2 per Cent.	CaO per Cent.
13.2	41.1	45.7

melting at 1316°C . This is approached in the regions marked X. Such slags must be very sensitive, as at the hearth temperatures the effect of high superheating above their melting points on the silicon reduction is rapid.¹ As the SiO_2 content of such slags

¹ See paper by the author "On the Superheating of Slags and Metals during Refining, Smelting, and Alloying Operations," *Journal of the Society of Chemical Industry*, 1917, vol. xxxvi. (No. 14).

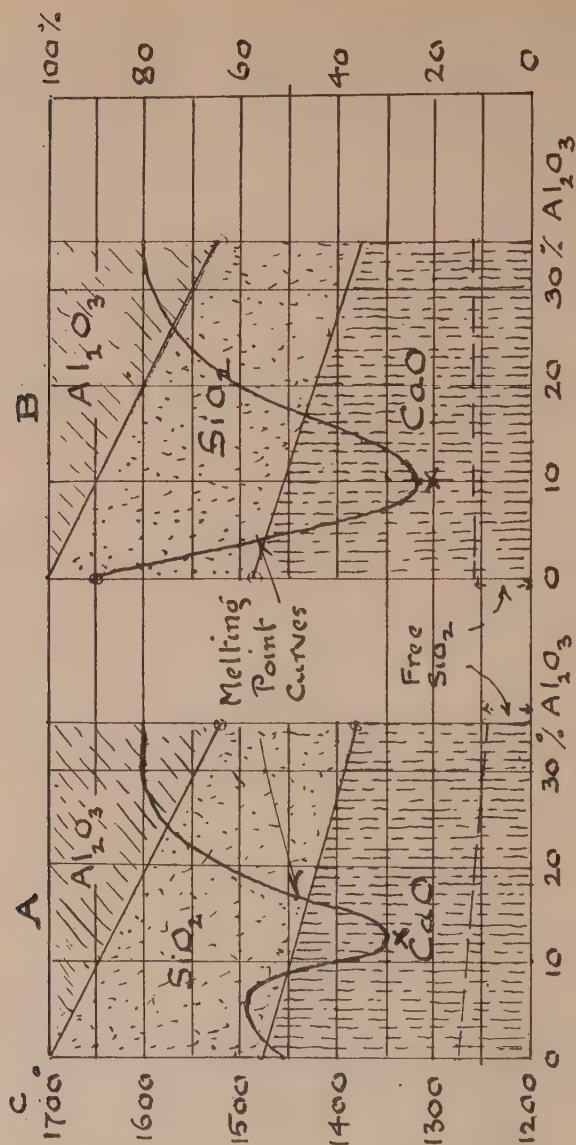


FIG 8.

(containing 10 to 15 per cent. alumina) falls the fusion point temperature rises quickly until with about 32 per cent. silica

this reaches about 1800°C . Hence the viscous nature of some, if not all, eutectic slags after desiliconising.

From the above it will be evident to students of the metallurgy of slags that the older methods of considering only the basicity ratio, with empirical modifications dependent on whether alumina acts as a base, a neutral, or an acid, do not meet the case. Fresh light is thrown on the subject when the constitution of blast-furnace and other slags is considered as a solvent of $2\text{RO}.\text{SiO}_2$ type in which are dissolved alumina and free active silica, the latter being the active agent in alloying the hearth metal.

CHARACTERISTICS OF COKE ASH SLAGS.

If the iron contents of coke ash be considered similarly to those of ores, the silica, lime, magnesia, and alumina may be taken as forming independent slags.

These slags are of the average constitution :

SiO_2 per Cent.	CaO and MgO per Cent.	Al_2O_3 per Cent.
55.0	5.0	40.0

with a melting point temperature of about 1580°C .

Such siliceous slags obviously have a powerful effect in the tuyere zone on the siliconising of the contact metal, and the result of using coke with high ash content is easily recognised.

The combined high moisture and ash contents of coke, not infrequently met with, have given blast-furnace managers a great deal of trouble during the past few years. The actual lowering of the calorific value of coke, owing to the heat required to drive off the moisture and to form, fuse, and superheat the slag resulting from the ash and its lime flux, is very considerable.

After allowing for the increased weight of slag made from the ash and its necessary flux and the heat required to drive off CO_2 from the added limestone, the total heat required by each pound of ash in the coke cannot be much less than 1350 B.T.U.

Taking this figure as a basis and 5760 B.T.U. as required to evaporate and dissociate one pound of moisture the graph Fig. 9 has been prepared. This diagram furnishes a ready means of arriving at the calorific value of a pound of coke whose ash and moisture contents are known. For example a coke containing 10 per cent. moisture and 15 per cent. ash would have a calorific

value of say 1005 B.T.U. per lb. or about 70 per cent. of the maximum pure carbon value. A good coke containing say 3 per cent. moisture and 5 per cent. ash would have a calorific

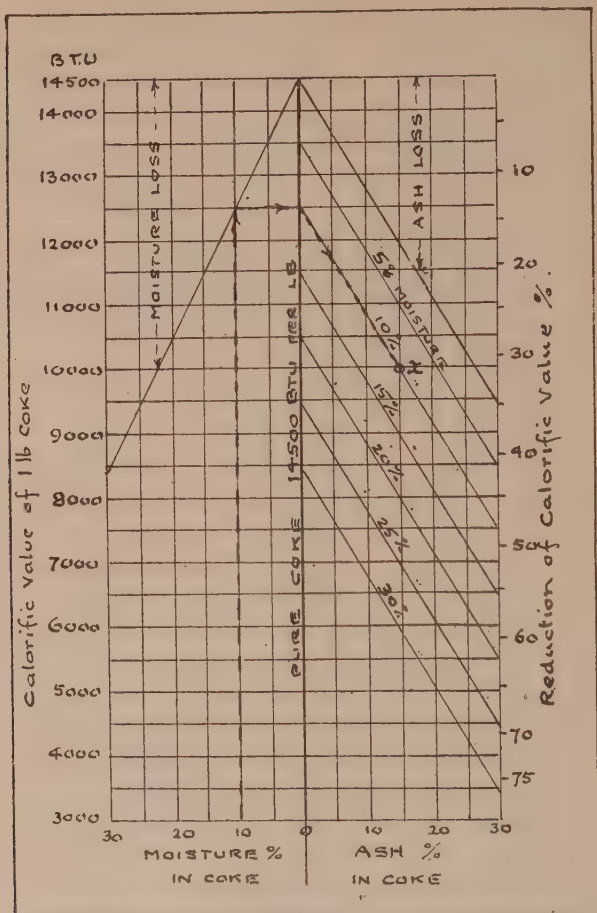


FIG. 9.

value of 13,200 B.T.U. Apart from the additional losses incidental to high ash and moisture contents in coke, of a mechanical nature, the use of the two cokes cited has, in a known case, meant the difference between 27 and 36 cwt. of coke per ton of iron smelted.

In the first case the loss in calorific value due to moisture is about 14 per cent., whilst that due to the ash is 16 per cent.

The graph indicates generally that each per cent. of moisture corresponds with a loss of 200 B.T.U., and for each per cent. of ash 168 B.T.U. per pound of coke.

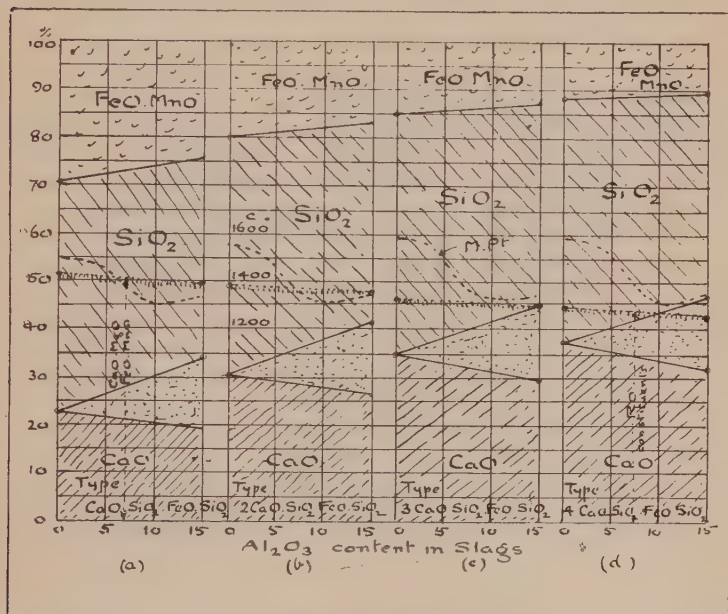


FIG. 10.

CUPOLA SLAGS.

In the cupola the working temperatures do not always reach the point where the meta-silicates in the slags pass into the ortho-silicate form. Hence it would appear that the constitution of these slags is then of the types :

- (a) $3\text{CaO} \cdot \text{SiO}_2 + \text{FeO} \cdot \text{SiO}_2 + n\text{Al}_2\text{O}_3$ } with free excess SiO_2 in solution.
 (b) $4\text{CaO} \cdot \text{SiO}_2 + \text{FeO} \cdot \text{SiO}_2 + n\text{Al}_2\text{O}_3$ }

By suitable lime additions slags of the composition (a) are often observed and have the lowest melting points when 10 to 15 per cent. alumina is present. Slags with from 5 to 7 per cent. alumina were found to melt at about 120°C . higher temperatures

than those containing 10 to 12 per cent. The graph, Fig. 10, has been prepared to illustrate the effect of varying the ratio $\text{CaO}.\text{SiO}_2$ in cupola slags whose alumina contents range from 0 to 15 per cent.

In the four groups the $\text{CaO}.\text{SiO}_2/\text{FeO}.\text{SiO}_2$ ratio is 1, 2, 3, and

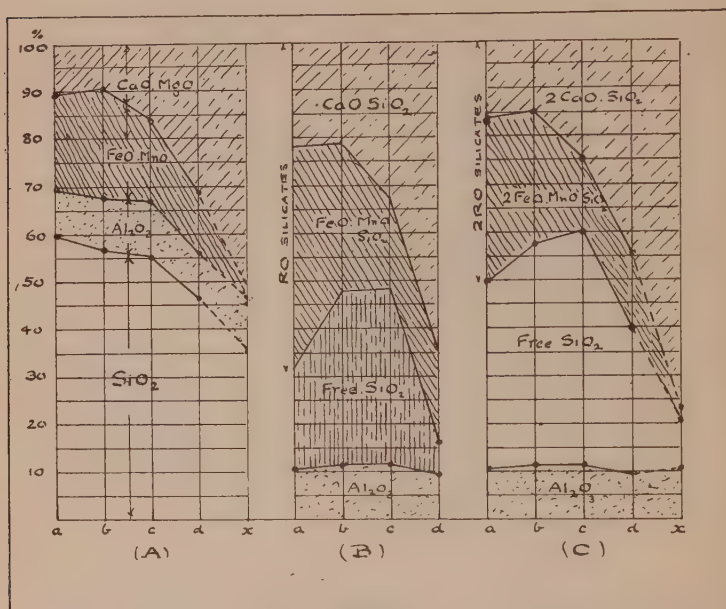


FIG. 11.

4 in (a), (b), (c), and (d) respectively. It will be noticed that the FeO content falls as the CaO rises, the melting points (approximate) falling as the alumina content increases.

Another diagram, Fig. 11, has been plotted from a series of cupola slags where the lime was progressively added. Graph (A) gives the analysis. Graph (B) is plotted to show the composition of the slags when considered as being built up of the meta-silicates $\text{CaO}.\text{SiO}_2$, $\text{FeO}.\text{SiO}_2$ with free SiO_2 and Al_2O_3 in solution. Graph (C) is similarly plotted on the hypothesis that the slags in their superheated condition are solutions of the $2\text{RO}.\text{SiO}_2$ silicates with free SiO_2 and Al_2O_3 in solution.

It will be seen that as the CaO content increases the character of cupola slags approaches that of blast-furnace slags. To

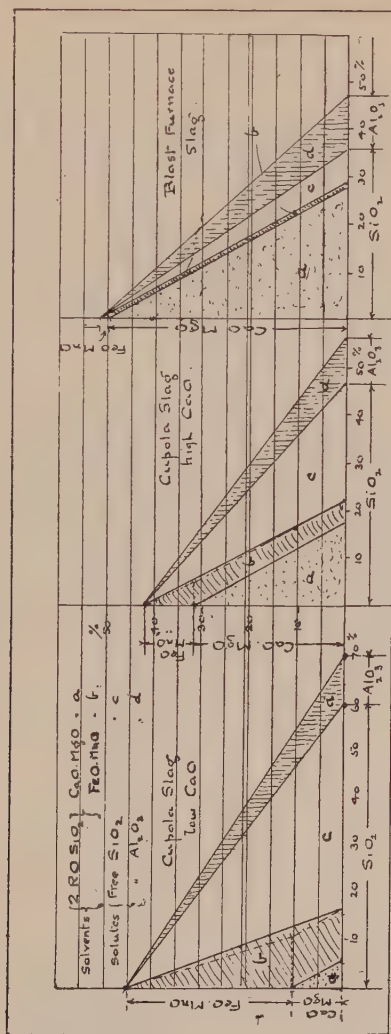


FIG. 12.

emphasise this fact the composition of blast-furnace slag x has been plotted on graphs (A) and (C).

The triangular graphs can be employed in the case of cupola slags and are useful in illustrating the passage from the ferrous

silicate type (viscous) to the more fluid calcic silicate variety which, as already shown, is closely related to the previously graphed blast-furnace type (see Fig. 12).

SUMMARY.

In the foregoing investigation the aim of the author has been to collate the data of many research workers in the slag field and to provide, by means of graphic methods, a clearer view of the slag solution theory and of its practical utility.

It is becoming increasingly necessary, if a true explanation of the reactions between slags and metals is to be arrived at, to ascertain the most probable composition of the liquid slags at the time such reactions are in progress.

Though the mineralogical character of the cold slags is of much use in slag research there is great danger lest it be concluded that the many crystalline transition products discovered in the cooled slags were present when they were more or less actively molten.

Further work is being undertaken on similar lines, in an endeavour to represent in graphic form the changes which take place in converter, puddling, and open-hearth processes.

The result of these further investigations the author hopes to place before the Institute in the near future.

DISCUSSION.

Dr. C. H. DESCH (Sheffield University) said that in Figs. 4 and 5 of Mr. Fletcher's paper the melting-point curves which were given were evidently the plane sections through the ternary diagram as constructed at the Geophysical Laboratory, and should correspond with portions of sections taken through that diagram; but on looking at them it scarcely seemed as if that were so. In Fig. 5 the melting-point curves which were given did not seem to be consistent with the ordinary ternary equilibrium diagram. Again, on p. 122 there was a reference to some groups in which iron oxide was present, and mention was there made of the influence of the composition on melting point. He would like to know from what data those statements had been derived, because the melting points of the mixtures containing iron oxides had really never yet been determined. The Geophysical Laboratory had made some attempt to determine them, but had found that, owing to the corrosive action of all the slags high in iron oxide, they could get no melting-point figures. He himself had made a great many attempts to investigate cinders and other slags high in iron oxides, but the corrosive action had been so great—the material eating away the crucible—that it was quite impossible to get any concordant melting points. Further, if the blast-furnace manager had to regulate the composition of his slag when dealing with a new ore—and, of course, that was a problem which had worried a good many of them when the change had to be made from, for example, Spanish ores to Lincolnshire and Northamptonshire ores—the data as to the fusibility could be derived directly from the Geophysical Laboratory's diagram. He knew of at least one blast-furnace manager who regularly determined the fusibility of his slag by reference to that diagram and comparison with the analyses. But that was done without assuming any hypothesis whatever as to the constitution of the liquid slag. From microscopical experiments and thermal analyses the compounds present in the slag after solidifying were known, but for the construction of the diagram it was not necessary to make any assumption as to the constitution of the liquid; and Shepherd, Rankin, and Wright refrained from making any such assumption. Mr. Fletcher had based his paper on certain assumptions, and he (Dr. Desch) would be glad if he would explain a little more exactly how his curves had been constructed, and what had led him to consider that his hypothesis as to the constitution of the liquid slag was actually justified.

Professor H. LOUIS, Member of Council, said Mr. Fletcher, in two passages on pp. 107 and 109, appeared to put forward definitely the

hypothesis that the slag consisted of a molten orthosilicate in which free silica and free alumina were dissolved. Obviously no one could say exactly in what state the molten material was, and the theory might be put forward that lime, alumina, silica, and everything else was dissolved in a molten silicate. It was quite impossible definitely to disprove such a theory, but he could not imagine how it could be possible, at that temperature, for free silica and free alumina to co-exist without combining. Everyone knew perfectly well that in nature, judging by the results after cooling, all the rocks that might be called huge natural slag deposits, were all silica-aluminates—alumina silicates combined with silicates of a base such as an alkali or an alkaline earth. There was no doubt in his mind that true aluminates of such bases could also be formed in a blast-furnace slag if there were an excess of alumina. On one occasion many years ago he had run a blast-furnace for a short time using a highly magnesian dolomite to flux an ore rich in alumina. He had had a large excess of magnesia present, and the slag in thin sections showed distinct crystals of spinel throughout the ground-mass. That was distinct evidence of the existence of an aluminate of magnesia, which in his opinion had formed as such at a high temperature and dissolved in the silicate from which it crystallised out on cooling. He could not imagine free alumina existing in the presence of bases or of silica in a state of simple solution. It was known that after slags had solidified they showed in many cases definite crystals in which the alumina was in combination. He might refer Mr. Fletcher to the vast amount of work which Professor Vogt had done on the subject. He would find that that authority listed a number of alumina-containing minerals which were produced by crystallising out from slags, and there was obviously no reason why it should be said that the alumina and the silica existed in a free state when they were molten, and then combined on crystallising out as the material solidified. A far more probable hypothesis was that there were those silicates, in which alumina was in a combined state, dissolved in the slag, and that they then naturally crystallised out on cooling. That afforded a far better explanation of the lowering of the temperature when alumina was present, because, although it was known that the melting point of alumina itself was high, it was much more logical to imagine a eutectic of a silicate of alumina and a silicate of lime forming and thus lowering the melting point, than to imagine that the melting point could be lowered by the simple solution of alumina and silica as such in the slag. He desired to record his opinion on this point as differing entirely from that of the author of the paper.

Mr. J. H. WHITELEY (Stockton-on-Tees) said he failed to see why Mr. Fletcher should make the statement contained in the second paragraph of the summary when, throughout the paper, he had assumed that the molten slag was a silicate of composition $2\text{RO}.\text{SiO}_2$ containing SiO_2 and Al_2O_3 in solution.

Mr. HALLIMOND (London) said that in regard to the mineralogical character of the slag, it was true that the minerals which crystallised out were not necessarily present—and in some cases were definitely not present—in the same form in the fluid melts. At the same time one had to do the best possible with the materials at hand, and at present practically the whole of the information with regard to fluid melts had to rest, as far as it rested on anything at all, upon the nature of the minerals which crystallised out. It would be fair to say that the only really definite piece of evidence on that point was some calculations made by American workers, in which they showed that the melting-point curve of the felspars was definitely that which would be anticipated for mixtures of substances of those compositions. The general question of the form of the melting-point curve had been debated for many years, but he believed that that was the first case in which a complete calculation had been possible for a silicate, and the result certainly seemed to indicate that these well-known compounds did not dissociate on melting.

Dr. W. ROSENHAIN (National Physical Laboratory) said he did not agree with Mr. Fletcher's hypothesis himself, because, to begin with, apparently members were asked to believe that some 60 per cent. of material was dissolved in 30 per cent. of some other material, and to call one a solute and another a solvent under those conditions was merely juggling with words. With regard, however, to the presence of silica in solution in some of those silicate melts, there was reason to believe that, in the high silicate slags which were commonly called glass, when they were under-cooled—that was to say, when crystallisation did not occur, and when they were under-cooled to the ordinary temperature—there were probably minute crystallites of free silica in suspension. If that were the case, he thought there was good reason to suppose that that silica really was held in solution as excess in some form of silicate when the material was hot. That was perhaps a kind of evidence on rather different lines from those suggested by Mr. Hallimond, but personally he thought it might be possible, by chilling some of those slags from the liquid state, to get some idea of the compounds that were present in them at a high temperature. Such evidence would be very difficult to interpret, particularly when the substances were complex and when they were too dark to be transparent and not easy to examine, but in the case of glass there were certain phenomena of fluorescence which suggested the presence of minute crystallites.

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CORRESPONDENCE.

Mr. FLETCHER, in reply, wrote that several speakers had taken the attitude that there was no need to base conclusions on the hypothesis that slags should be considered in their molten condition, on the ground

that it was impossible to arrive at their true constitution when fluid. He had based his hypothetical analyses in the molten state on the fact that the meta-silicates CaO.SiO_2 and FeO.SiO_2 , on being heated well above their melting points, tended to become ortho-silicates with free silica in solution, thus :



The presence of olivine and fayalite in cooled slags having a meta-silicate composition would appear to prove the presence of the ortho-silicates at the higher temperatures.

Dr. Rosenbain had suggested that by quick cooling or quenching of the slags the free silica, which he recognised might be present, should be more readily defined. He (Mr. Fletcher) considered that the presence of free silica in certain cooled blast-furnace slags argued, analogously to similar behaviour during the cooling of certain molten refractories, the presence of the ortho-silicates in the molten condition.

The fact that when a blast-furnace was making a run of increasingly siliceous iron the slag became more basic in character pointed to the truth of the assertion that during working conditions slags tended to become inert, *i.e.*, the ratio of acid oxygen to basic oxygen content in the slags tended towards unity.

Professor Louis objected to the assumption or hypothesis that alumina existed in the free state in slags. He (Mr. Fletcher) had not taken that position ; but, in considering alumina as having no active effect—not being dissociated at blast-furnace temperatures—he had stated that working slags might be safely considered as solutions of alumina and free silica and ortho-silicates of lime and magnesia (see p. 112). It was quite probable that the alumina was present in the fluid slags as aluminate of lime and, if the alumina was then acting as an acid oxide, the tendency during the reduction of silicon from the slag might be to form a lime aluminate of the type $3\text{CaO.Al}_2\text{O}_3$ —of neutral or inert character.

In such case the amount of free silica in the primary slags would be increased and the slag constitution could be defined as built up of the neutral ortho-silicates of lime and magnesia, the neutral lime or lime-magnesia aluminate, and free silica. He had in fact estimated a number of blast-furnace slags on that hypothesis with encouraging results. For example. A slag of estimated composition :

Ortho-silicate, 2CaO.SiO_2	.	.	.	66.6	per cent.
Lime-aluminate, $3\text{CaO.Al}_2\text{O}_3$	.	.	.	33.3	„

would have the corresponding analysis :

$\text{CaO} = 62.7$ per cent. ; $\text{SiO}_2 = 11.7$ per cent. ; $\text{Al}_2\text{O}_3 = 25.6$ per cent.

By suitable free SiO_2 addition the final slag analysis became :

$\text{CaO} = 47.2$ per cent. ; $\text{SiO}_2 = 33.5$ per cent. ; $\text{Al}_2\text{O}_3 = 19.3$ per cent.

which agreed with the composition of many normal working slags.

A closer examination of that phase of molten slag constitution would appear to point to the possibility that blast-furnace slags in the molten condition, before silicon reduction, contained the lime-magnesia ortho-silicate and the tri-calcic aluminate in the proportion of from 0·3 : 1 to 1 : 1 with excess silica sufficient to yield about 38 to 45 per cent. total SiO_2 in the primary slag.

TABLE A.

	Constituent $2\text{CaO}.\text{SiO}_2$ Parts.	Constituent $3\text{CaO}.\text{Al}_2\text{O}_3$ Parts.	CaO_2 per Cent.	SiO_2 per Cent.	Al_2O_3 per Cent.
A	1	0	65·1	34·9	0·0
B	9	1	64·6	31·5	3·9
C	4	1	64·3	28·0	7·7
D	3	1	64·1	26·2	9·6
E	2	1	63·8	23·4	12·8
F	1	1	63·2	17·5	19·3
G	1	2	62·7	11·7	25·6
H	1	3	62·4	8·7	28·9
I	1	4	62·2	7·0	30·8
J	1	9	61·9	3·5	34·6
K	0	1	61·5	0·0	38·5

The Table A above gave the analyses of a range of mixtures of the aforementioned silicate and aluminate. The addition of free silica to mixtures F, G, H, and I so as to yield about 47 per cent. CaO in the slags was illustrated in the following analyses :

	F.	G.	H.	I.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
CaO . . .	47·2	47·2	47·2	47·2
SiO_2 . . .	38·3	33·5	31·0	29·6
Al_2O_3 . . .	14·5	19·3	21·8	23·2
Free SiO_2 . . .	25·2	24·7	24·4	24·3

In the absence of any data establishing the presence of the tri-calcic aluminate in blast-furnace slags—though that aluminate did appear in slag cements—he did not feel free to advance that hypothesis in his paper. The presence of spinel in cooled slags containing MgO , as referred to by Professor Louis and noted by Vogt, Gredt, and others, would appear to confirm the view that the aluminates of lime and magnesia were present in the liquid slags. Spinel might be a transition product crystallising out from the $3\text{RO}.\text{Al}_2\text{O}_3$ on slow cooling.

There was, however, a good deal of practical evidence in the analyses of slags other than blast-furnace in favour of the theory that under
1921—i.

high temperature conditions, when the slags were superheated beyond their lowest fusion points, the inert condition typified by the ortho-silicate $2\text{CaO}.\text{SiO}_2$ and the tri-calcic aluminate $3\text{CaO}.\text{Al}_2\text{O}_3$ was approached.

The American geophysical results would seem to indicate that those inert forms were the stable ones.

If the excess silica were dissolved in a solvent composed of the $2\text{CaO}.\text{SiO}_2$ and $3\text{CaO}.\text{Al}_2\text{O}_3$ stable (?) constituents in blast-furnace slags when molten, then Dr. Rosenhain's reproach that he presupposed the case of the smaller dissolving the larger fell to the ground. Indeed, on p. 109 it was distinctly stated that the solvent silicates were present in the order of 60 to 75 per cent. If the aluminate was present as $3\text{CaO}.\text{Al}_2\text{O}_3$ the solutes SiO_2 , CaS , &c., would amount to 25 to 30 per cent.

In a future communication the author hoped to show that that hypothesis might explain the molten constituency and the mechanism of the reactions in puddling and other slags.

In answer to Dr. Desch it should be stated that the graphs Figs. 6 and 7 were constructed in the manner described at the foot of p. 114, the basal ortho-silicate triangles being drawn as in Fig. 2. He had found that the geophysical solid $\text{CaO}.\text{SiO}_2.\text{Al}_2\text{O}_3$ diagram did not cover actual normal blast-furnace slags, as a careful examination of Fig. 4 would show. Hence in Fig. 5 the melting point curves had been obtained by interpolation and could only be considered as approximate. They did show the relative effects of alumina additions to the ortho-silicate and could not be far from the truth, indicating that when the CaO content was between 45 and 50 per cent. the lowest melting points were reached. In reply to Mr. Hallimond he agreed that Fig. 1, which was self-explanatory, might be extended so as to cover certain low grade iron ores of probable volcanic origin. The work of Dr. Lessing in connection with fuel ash composition was important as relating to the influence of geological phenomena on adjacent fuel and ore beds. The analogy between certain igneous rocks and ferrous slags, *i.e.*, basalt and chlorite schist, was particularly interesting and suggestive.

He wished to thank Mr. Whiteley for the valuable work he had done on slag problems, which, with the similarly important results of Dr. McCance's researches, had thrown so much light on difficulties he had himself encountered in his own investigations.

Finally, he desired to confirm Dr. Desch's experience in regard to the difficulty of obtaining true fusion points of cupola slags. The approximate melting point temperatures given in Fig. 10 had been arrived at by observation of the actual slags running from the slag spouts of the cupolas.

Crucible determinations of synthetic slags of that nature were extremely difficult.

Iron and Steel Institute.

THE PREVENTION OF HARDENING CRACKS AND THE EFFECT OF CONTROLLING RECALESCENCE IN A TOOL STEEL.

BY SHIPLEY N. BRAYSHAW (MANCHESTER).

ABSTRACT OF PAPER.

THE paper describes a research carried out on a tool steel containing about 1.1 per cent. of carbon, 0.8 of tungsten, and 0.2 of chromium. The changes that occur during the halts in heating and in cooling were investigated by means of a large number of bars which, after soaking for various periods of time at temperatures near the critical points, were quenched in water. The condition of the steel after quenching showed the progress of the change; and some of the results suggest that, both in heating and in cooling, the changes, Ac1.2.3 and Ar3.2.1, take place in stages which may be separated one from another if sufficient time be allowed for the process.

A second series of bars, similarly heat-treated, was cooled in sand instead of being water-quenched. All these sand-cooled bars were finally hardened by one standard process. These bars lengthened or shortened on hardening, in response to the maximum temperature of the previous annealing, and to the progress that had been made in the slow recalescence during that annealing. The behaviour of the hardened bars under bending stress was also found to have been determined by the heat treatment prior to the hardening. Light is thrown upon the subject by a comparison between those water-quenched bars referred to in the previous paragraph, and these bars which were sand-cooled from the heat treatment and then hardened.

The tendency of the steel to crack in hardening was correlated to the various results from the bars by means of a series of milling cutters purposely made of a design extremely difficult to harden. The milling cutters were machined out of blanks which had been heat-treated along with the bars. After the machining, the cutters all underwent the same standard hardening without

any intervening process. The resulting cracks were found to occur in reasonable sequence with the treatment and with the results from the bars. When sufficient time was allowed for the heat treatment, within a certain range of temperature, the steel reached a condition in which the liability to crack in hardening was greatly reduced.

The following also are some of the matters arising out of the research. There was a remarkable uniformity in the modulus of elasticity of the hardened bars which differed greatly in other respects. Cutters which broke badly in hardening were generally made from blanks in which the ratio of the Brinell figure to the Shore figure was comparatively high. Progressive changes in length on successive days after hardening are referred to. A suggestion is made for a standard hardening test.

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PART I.

INTRODUCTION.

The experimental work described in this paper was carried out for the purpose of investigating the changes that occur in a

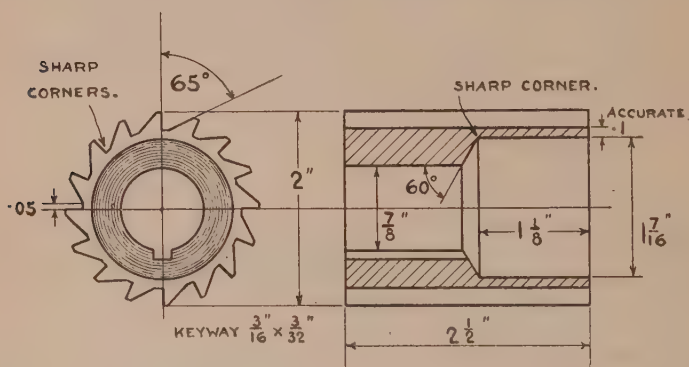


FIG. 1.

low-tungsten tool steel when heated or cooled under strict control ; and further, to ascertain the bearing of these changes upon the behaviour and condition of the steel when subsequently hardened. The work is a continuation of a research carried out during the past seventeen years. In the first instance the author set out to investigate the cause of some hardening breakages ; for which purpose experiments were made with test cutters as shown in Fig. 1, although rigid limits of size were not then fixed, and some of the cutters had no keyway. These cutters were so designed as to present the utmost difficulty in hardening, and any treatment found to be successful for them might safely be adopted for general use. The results led to further experiments, which again pointed the way to an ever-widening field

for research. For some years attention was concentrated mainly upon the treatment of the test cutters after they had been machined up. They were annealed in many ways. Cutters, both annealed and unannealed, were heated and quenched by hundreds of treatments, which were duly recorded with the results arising therefrom. Altogether nearly a thousand such cutters have been made for experimental purposes. Some of these are illustrated in Fig. 2, Plate VI. Various kinds of hardening cracks are shown, and one sound cutter is included. It was found possible to harden these cutters with considerable success and by methods which differed greatly one from another; but unfortunately the successful treatments demanded such accuracy of control as to limit their usefulness. Meanwhile observations were continued over a course of years by making and hardening one test cutter from each of a number of bars $2\frac{1}{8}$ inch black diameter. These bars of the steel in question, annealed by the steelmaker, were received at the rate of one every few weeks. They were found to be very uniform so far as machining properties were concerned, and there was reason to believe that the analysis was remarkably constant; yet, when the cutters made from them were hardened with the least possible variation of treatment by heating in a salt-bath (at 760°C.) and quenching in cold water, they differed greatly in their behaviour. The treatment was drastic, and it was only to be expected that every cutter would be broken; but the breakages varied in character and in some cases were very much worse than in others. At the same time the appearance of the fracture was almost always good, and such as would be universally pronounced to indicate good steel well treated. On one occasion a surprising result was obtained. A test cutter, taken from a bar as received in the ordinary routine, hardened without a flaw on being subjected to the usual treatment. This significant occurrence directed the attention of the author to the desirability of concentrating attention on the annealing of the bars or blanks, rather than on the treatment of the machined cutters; and work proceeded on these lines whenever opportunity could be found for research, many interesting results being obtained from time to time. Finally it was decided to conduct a series of experiments to cover a field, clearly defined

and complete within its own limits, which should co-ordinate the results obtained piecemeal over a long period. A research on these lines has been carried out within the last two years, and forms the sole subject-matter of this paper. Complete records are available of all the work done, including pyrometer charts, records showing the position of each piece in the furnaces for every process, and many other details. All the results obtained have been brought under review, and prominence has been given to irregularities as much as to results which fulfilled expectations. The whole of the results shown in Tables VII. and VIII. have been rearranged, in various groupings, in numerous tables and diagrams not reproduced in this paper but which are available for inspection.

The following is an outline of the scheme and scope of the research. The halts Ac1.2.3 and Ar3.2.1 were examined, as a matter of course, by taking heating and cooling curves, which, however, were only auxiliary to the main work. An exhaustive investigation of the halts was accomplished by ascertaining some of the changes which occurred when the steel was maintained at certain fixed temperatures. For this purpose many heats were carried out in triplicate. One cutter blank and two test bars (Fig. 3, Plate VII.) received exactly the same heat treatment, namely, the careful maintenance of the pieces, for various lengths of time, with or without previous heating, at temperatures in the neighbourhood of the change points. The cutter blank and one test bar were then cooled in sand, whilst the other bar was quenched in water. After this they were all tested for hardness, and the bars were measured for change in length. The blank was machined up into a test cutter, which was hardened by a standard process to show the cracks likely to occur as a result of the previous treatment. The sand-cooled bar was wanted, not so much for its own sake, as for the important relation which it bore, after a standard hardening, to the hardened cutter made from the corresponding blank. The water-quenched bar¹ clearly showed the progress of the change Ac1.2.3 or Ar3.2.1,

¹ The expression "water-quenched bars" is used to denote the bars which were water-quenched from the heat treatment, in contradistinction to those which were sand-cooled. The bars were finally hardened by water-quenching, but they are then spoken of as bars which underwent the standard hardening treatment.

as the case might be, and the amount of the difference in hardness between the sand-cooled and the water-quenched bars was instructive. In actual practice the test cutters were omitted

TABLE I.

Heat Treatment.										Method of Cooling			
Temperature.	Time—Hours.												
	$\frac{1}{8}$.	$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	4.	8.	12.	16.				
739°	{	B5	B6	B7	B8	{ B9 ^a } { B9 }	B10	B11	B12	...	{	Water	
		B13	...	B14	...	B15	...		{	Sand
		...	...	...	C13	...	C14	...	C15	...
732°	{	{ B16 ^a } { B16 }	{ ... } { ... }	{ B17 ^a } { B17 }	{ B18 }	{ B19 ^a } { B19 }	{ B20 }	{	Water	
		B21 ^a	...	{ B22 ^a } { B22 }	{ ... }	{ B24 ^a }	{ B25 }		{	Sand
		...	...	...	C21 ^a	...	{ C22 ^a } { C22 }	{ C23 }	{ C24 ^a } { C24 }	{ C25 }
725°	{	B26	...	B27	B28	B29	B30	{	Water	
		B31	...	B32	B35		{	Sand
		...	...	...	C31	...	C32	C33	C34	C35
718°	{	B36	...	B37	...	B38	B39	{	Water	
		B40	...	B41	B43		{	Sand
		...	...	...	...	...	...	...	C42	C43

"B" Series of numbers refers to test-bars.

"C" " " " " test-cutter blanks.

All the bars and cutter blanks referred to above were first normalised by heating to 825° C. for 1 hour and cooling in air; then followed the heat treatment shown above; and finally all of them, with the exception of bars B9a, B16, B17, B18, B19, B20, B22, and B25, were hardened by heating to 760° C. and quenching in water.

In addition to the above, B1, B2, C1, and C2 were hardened without previous normalising, and without heat treatment. B3, B4, C3, and C4 were hardened after normalising, but without heat treatment.

in many cases on account of expense, the bars only being carried through to indicate the progressive changes in the steel.

In more detail, it may be stated¹ that the change Ac1.2.3¹ is taken for the moment as occurring at 738° C. for this steel;

¹ Throughout the paper the symbol "Ac1.2.3" is used, and is spoken of as "a change occurring at 738°"; but these terms must be taken as expressions convenient for the moment, without any implication as to the nature, or mode of occurrence, of the change or changes in question.

and one series of treatments consisted of heating, for periods of time varying from $7\frac{1}{2}$ minutes to 16 hours, to a temperature

TABLE II.—*Maximum Temperature, 750° C.*

First Furnace.	Second Furnace.											Method of Cooling.
	Temperature.	Time—Hours.										
		$\frac{1}{8}$.	$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	3.	4.	8.	12.	16.	
B44, 750°-1 hour												Water
B45 and C45— 750°-1 hour												Sand
B46 to B97 and C54 to C97 were all heated alike to 750° for one hour and then trans- ferred as quickly as possible to the second furnace, which was already at the tem- perature shown	732°	B46	B47	B48	B49	B50	...	B51	B52	B53	...	Water
		...	...	...	B54	...	...	B55	...	B56	...	} Sand
		...	...	...	C54	...	...	C55	...	C56	...	
	725°	B57	B58	B59	B60	B61	...	B62	B63	B64	B65	Water
		...	B66	...	B67	...	...	B68	...	B69	B70	} Sand
		...	C66	...	C67	...	...	C68	...	C69	C70	
	718°	B71	B72	B73	B74	B75	...	B76	B77	B78	...	Water
		...	B79	...	B80	...	...	B81	...	B82	...	} Sand
		...	C79	...	C80	...	...	C81	...	C82	...	
	706°	...	B83	B84	B85	B86	...	...	...	...	...	Water
		...	...	B87	B88	B89	...	...	...	...	...	} Sand
		...	...	C87	C88	C89	...	...	...	...	...
	Start at 740°; cool uniformly to 718°	...	...	...	...	B90	...	...	B91	...	...	Water
		...	...	...	...	B92	...	...	B93	...	...	} Sand
		...	...	...	...	C92	...	...	C93	...	...
	Start at 740°; cool uniformly to 706°	...	...	...	...	...	B94	...	...	B95	...	Water
		...	...	...	...	...	B96	...	...	B97	...	} Sand
		...	...	...	...	...	C96	...	...	C97	...	

"B" Series of numbers refers to test-bars.

"C" " " " " test-cutter blanks.

All the bars and cutter blanks referred to above were first normalised by heating to 825° for 1 hour and cooling in air; then followed the heat treatment shown above; and finally they were all hardened by heating to 760° C and quenching in water.

of 739°, 732°, 725°, or 718° C., followed by quenching or cooling as explained above. There were also four series of treatments, in each of which the pieces were first heated for one hour to a temperature well above Ac1.2.3 (the temperature was 750°, 800°, 850°, or 900° C.). After this hour's heating the pieces were quickly transferred to a second furnace, for times varying

from $7\frac{1}{2}$ minutes to 16 hours, at a temperature of 732° , 725° , 718° , or 706° C. In some cases the temperature in the second

TABLE III.—*Maximum Temperature, 800° C.*

First Furnace.	Second Furnace.											Method of Cooling.		
	Tempera- ture.	Time—Hours.												
		$\frac{1}{8}$.	$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	3.	4.	8.	12.	16.			
B98, 800°-1 hour												Water		
B99 and C99— 800°-1 hour												Sand		
B100 to B155 and C108 to C155 were all heated alike to 800° for one hour and then trans- ferred as quickly as possible to the second furnace, which was already at the tem- perature shown	732°	{	B100	B101	B102	B103	B104	...	B105	B106	B107	...	Water	
			B108	B109	...	B110	...	{	Sand
			...	...	...	C108	...	...	C109	...	C110	...
	725°	{	B111	B112	B113	B114	B115	...	B116	B117	B118	...	Water	
			...	B119	...	B120	B121	...	B122	...	{	Sand
			...	C119	...	C120	...	...	C121	...	C122	...
	718°	{	B123	B124	B125	B126	B127	...	B128	B129	B130	B131	Water	
			...	B132	...	B133	B134	...	B135	B136	{	Sand
			...	C132	...	C133	...	...	C134	...	C135	C136
	706°	{	...	B137	B138	B139	B140	Water	
			B141	B142	B143	{	Sand
			...	...	C141	C142	C143	...	...	...	...	...
	Start at 740°; cool uniformly to 718°	{	B144	B145	...	B146	B147	Water	
			B148	B149	...	B150	B151	{	Sand
			...	...	...	C148	C149	...	C150	C151	...	...
	Start at 740°; cool uniformly to 706°	{	B152	B153	...	Water	
			B154	B155	...	{	Sand
			...	...	...	...	...	C154	...	...	C155	...

"B" Series of numbers refers to test-bars.

"C" " " " " test-cutter blanks.

All the bars and cutter blanks referred to above were first normalised by heating to 825° for 1 hour and cooling in air; then followed the heat treatment shown above; and finally they were all hardened by heating to 760° C. and quenching in water.

furnace fell in a given time, through a certain range, instead of remaining fixed for the given period. After soaking in the second furnace, the pieces were quenched in water, or cooled in sand, as desired. When the bars had undergone any of the treatments referred to above, the hardness and change in length were ascertained; then all of them, with eight exceptions,

were hardened by one standard process ; after which the hardness, and change in length, were again observed ; and lastly,

TABLE IV.—*Maximum Temperature, 850° C.*

First Furnace.	Second Furnace.											Method of Cooling.
	Temperature.	Time—Hours.										
		$\frac{1}{8}$.	$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	3.	4.	8.	12.	16.	
B156, 850°-1 hour												Water
B157 and C157— 850°-1 hour												Sand
B158 to B207 and C166 to C207 were all heated alike to 850° for one hour and then trans- ferred as quickly as possible to the second furnace, which was already at the tem- perature shown	732°	B158	B159	B160	B161	B162	...	B163	B164	B165	...	Water
		...	...	...	B166	...	...	B167	...	B168	...	} Sand
		...	...	...	C166	...	...	C167	...	C168	...	
	725°	B169	B170	B171	B172	B173	...	B174	B175	B176	...	Water
		...	B177	...	B178	...	...	B179	...	B180	...	} Sand
		...	C177	...	C178	...	...	C179	...	C180	...	
	718°	B181	B182	B183	B184	B185	...	B186	B187	B188	...	Water
		...	B189	...	B190	...	...	B191	...	B192	...	} Sand
		...	C189	...	C190	...	...	C191	...	C192	...	
	706°	...	B193	B194	B195	B196	...	...	...	...	...	Water
		...	...	B197	B198	B199	...	...	...	...	...	} Sand
		...	...	C197	C198	C199	...	...	...	...	...
	Start at 740°; cool uniformly to 718°	...	...	...	...	B200	...	...	B201	...	...	Water
		...	...	...	...	B202	...	...	B203	...	...	} Sand
		...	...	...	...	C202	...	...	C203	...	...
	Start at 740°; cool uniformly to 706°	...	...	...	...	...	B204	...	...	B205	...	Water
		...	...	...	...	...	B206	...	...	B207	...	} Sand
		...	...	...	...	...	C206	...	...	C207	...	

"B" Series of numbers refers to test-bars.

"C" " " " " test-cutter blanks.

All the bars and cutter blanks referred to above were first normalised by heating to 825° for 1 hour and cooling in air ; then followed the heat treatment shown above ; and finally they were all hardened by heating to 760° C. and quenching in water.

the hardened bars were broken under bending stress. Special interest attaches to a comparison between the results so obtained from the bars, and the hardening cracks occurring in the cutters which, in the blank, underwent corresponding heat treatments. The total number of test bars was 262 and of test cutters 102. A complete idea of the treatments given may be gathered

from Tables I. to V. All the hardness and bending tests, involving an enormous amount of work, were undertaken by

TABLE V.—*Maximum Temperature, 900° C.*

First Furnace.	Second Furnace.											Method of Cooling.
	Tempera- ture.	Time—Hours.										
		$\frac{1}{8}$.	$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	3.	4.	8.	12.	16.	
B208, 900°-1 hour												Water
B209 and C209— 900°-1 hour												Sand
B210 to B261 and C218 to C261 were all heated alike to 900° for one hour and then trans- ferred as quickly as possible to the second furnace, which was already at the temper- ature shown	732°	B210	B211	B212	B213	B214	...	B215	B216	B217	...	Water
		...	...	...	B218	...	...	B219	...	B220	...	} Sand
		...	...	...	C218	...	...	C219	...	C220	...	
	725°	B221	B222	B223	B224	B225	...	B226	B227	B228	...	Water
		...	B229	...	B230	...	...	B231	...	B232	...	} Sand
		...	C229	...	C230	...	...	C231	...	C232	...	
	718°	B233	B234	B235	B236	B237	...	B238	B239	B240	B241	Water
		...	B242	...	B243	...	...	B244	...	B245	B246	} Sand
		...	C242	...	C243	...	...	C244	...	C245	C246	
	706°	...	B247	B248	B249	B250	...	...	...	...	...	Water
		...	...	B251	B252	B253	...	...	...	...	...	} Sand
		...	...	C251	C252	C253	...	...	...	...	...
	Start at 740°; cool uniformly to 718°	...	...	...	...	B254	...	...	B255	...	...	Water
		...	...	...	...	B256	...	...	B257	...	...	} Sand
		...	...	...	...	C256	...	...	C257	...	...
	Start at 740°; cool uniformly to 706°	...	...	...	...	...	B258	...	...	B259	...	Water
		...	...	...	...	...	B260	...	...	B261	...	} Sand
		...	...	...	...	...	C260	...	...	C261	...	

"B" Series of numbers refers to test-bars.

"C" " " " " test-cutter blanks.

All the bars and cutter blanks referred to above were first normalised by heating to 825° for 1 hour and cooling in air; then followed the heat treatment shown above; and finally they were all hardened by heating to 760° C. and quenching in water.

Dr. W. H. Hatfield, and were carried out with great care and thoroughness at the Brown-Firth Research Laboratories.

It is suggested that, at this point, members should read Part IV., "Conclusion," beginning on p. 196. They will then understand the significance of Parts II. and III., and what they are leading up to, and will accordingly follow them the more readily.

PART II.

DETAILS OF THE EXPERIMENTAL WORK.

Necessity for Examining the Methods of Working.

More than 3700¹ recorded results were obtained from the test bars alone; and that some of these should be erratic was in accord with reasonable expectation, in view of the fact that many of the bars were very hard after the heat treatment, and nearly all of them underwent a final thorough hardening. The test cutters could not be expected to give fully consistent results, considering the elusive nature of hardening cracks. There must have been initial irregularities in the steel as received by the author; and further discrepancies must have originated in the machining, heating, and quenching of the pieces; and also, no doubt, though to a minor degree, in the testing. In seeking explanations of the results obtained it is obviously necessary to examine the methods of working throughout in considerable detail, as much may depend upon apparent trifles, and accordingly the following particulars are given of the experimental work.

Steel.

All the test bars were made from bars annealed in the usual way by the steelmaker, and of about the following black size, $\frac{21}{32}$ inch by $\frac{27}{32}$ inch, to finish $\frac{9}{16}$ inch by $\frac{3}{4}$ inch. The total quantity of steel supplied for this purpose was $2\frac{1}{2}$ cwts., all made from one ingot.

TABLE VI.—*Analysis of Steel.*

	For Cutters, Per Cent.	For Bars, Per Cent.
Carbon	1.14	1.13
Manganese	0.34	0.35
Silicon	0.15	0.14
Sulphur	0.036	0.033
Phosphorus	0.018	0.017
Nickel	nil	nil
Chromium	0.20	0.16
Tungsten	0.87	0.74
Vanadium	trace	trace

¹ This does not include such figures as were obtained by the numerous successive readings of stress and deflection under bending test. Neither does it include derived figures such as those for the modulus, energy, or Brinell-Shore ratio.

All the test cutters were made from about $2\frac{3}{4}$ cwts. of bars, annealed in the usual way by the steelmaker, and about $2\frac{1}{8}$ inch black diameter, to finish 2 inches, all made from one ingot. The analysis for both bars and cutters is shown in Table VI. Comparisons are frequently made between corresponding bars

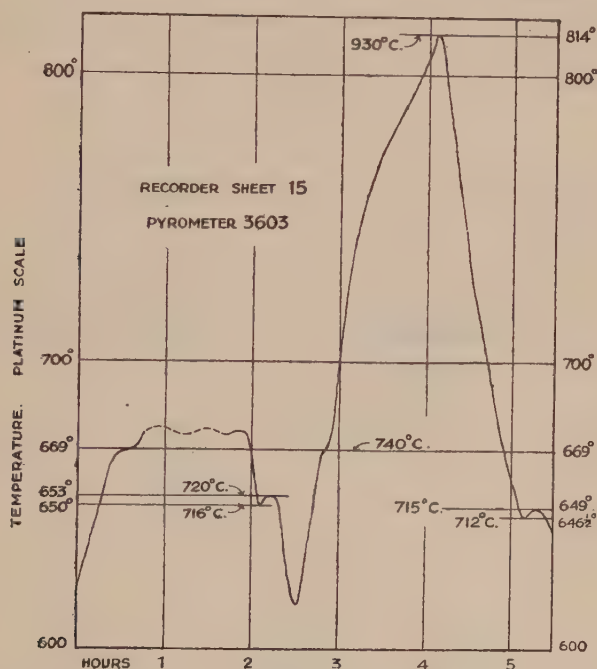


FIG. 4.

and cutters as though they were made of exactly similar steel, whereas there is an appreciable difference in the combined content of chromium and tungsten. Taken all round, the two analyses agree very closely, and reflect credit on the steelmaker. Seventeen of the cutter blanks were noted, during turning, as having flaws on the surface of the steel. Some of these flaws were very slight, and some were bad; but they did not in any case appear noticeably to affect the cutters on hardening, and no account is taken of them.

Heating and Cooling Curves.

Several heating and cooling curves, of which examples are given in Fig. 4, were taken with a Callendar Recorder from a piece of the steel $2\frac{1}{8}$ inches diameter and 4 inches long, in a fireclay muffle as shown in Fig. 5. The halt Ac1.2.3 occurred at about 738° , and Ar3.2.1 at 712° to 716° C. This subject is dealt with more fully in Appendix I.

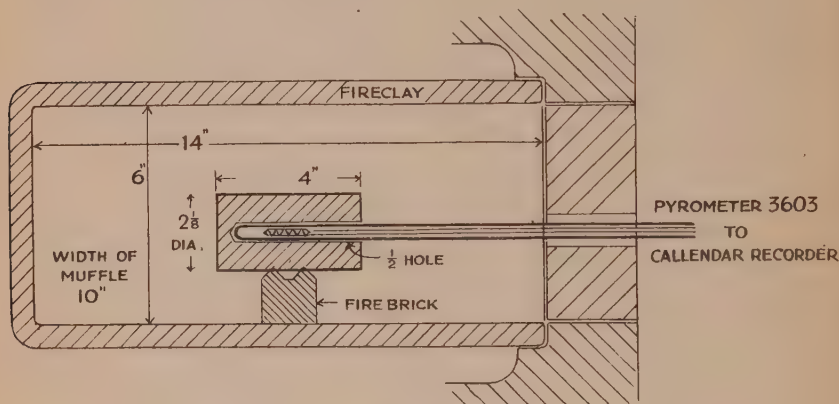


FIG. 5.

Test Bars.

262 test bars were made $\frac{3}{4}$ inch wide, $\frac{9}{16}$ inch deep, and 5.9 inches long, with the ends rounded to facilitate measurement (see Fig. 6). About a dozen of the bars were machined smaller than the bottom limits shown. Near one end a wire was looped through a drilled hole, for handling the bars when hot (see Fig. 7, Plate VII.). The weight, as sawn from the black bars, was about 15 ounces, and finished, 11 ounces.

Cutter Blanks and Test Cutters.

102 cutter blanks were sawn from the bars, and turned about 2.6 inches long, the black diameter, about $2\frac{1}{8}$ inches, being untouched (Fig. 3, Plate VII.). The test cutters were made 2 inches

diameter, $2\frac{1}{2}$ inches long, with a hole and recess as shown in Fig. 1. The internal corners of the recess and the roots of the teeth were left sharp to increase the liability to crack in hardening. In order to ensure that the hardening cracks should depend upon the condition of the steel, and not upon differences of machining, the thickness of metal between the recess and the bottom of the teeth was made one-tenth of an inch as accurately as possible. Inevitably this dimension was subject to slight variations which might appreciably affect the results. The weight of the blanks was about $2\frac{1}{2}$ lbs., and of the finished cutters

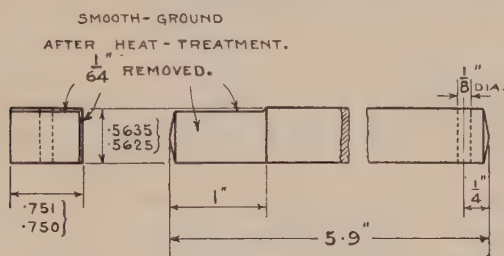


FIG. 6.

about 1 lb. The cutters were not numbered consecutively, but bore the same numbers as the corresponding bars.

Furnaces.

The heating for the various processes was done in two salt-bath furnaces heated by coal-gas. The furnace used for temperatures of 750°C . and over was fitted with a pot made of a nickel-chrome alloy, and the other furnace for lower temperatures had a cast iron pot. Both pots were 11 inches diameter inside and 16 inches deep. The pots were filled, within about 3 inches of the top, with pyromelt composed mainly of chlorides of barium, potassium, and sodium. The weight of pyromelt was about 1 cwt., and of each pot about $1\frac{1}{2}$ cwt. The total weight of each pot and its contents was therefore about $2\frac{1}{2}$ cwt., which was sufficient to prevent rapid fluctuations of temperature. The maintenance of one temperature for a long time was also assisted by a mass of brickwork about 5 inches

thick surrounding the pot. Each furnace was fitted with a tray designed for the purpose of the research (see Fig. 7, Plate VII.).

Pyrometers.

The first furnace temperatures of 750°, 800°, 850°, and 900° C., and the normalising temperature of 820° C., were shown by a "Thread" Recorder in conjunction with a "Titan" thermocouple, which is an iron-constantan couple made of wires $\frac{3}{16}$ inch diameter. The cold junction was kept in oil in a thermos flask in which a temperature of 20° C. was maintained, usually within a degree or two, but on two occasions the temperature fell to 16°. The range from 700° to 950° C. was represented by a length of $3\frac{1}{8}$ inches on the chart, so that $\frac{1}{8}$ inch represented 10° C. This did not allow of very accurate readings; but it was good enough; as great accuracy with respect to these temperatures was presumably not important.

The second furnace temperatures and the single-heat temperatures of 706°, 718°, 725°, 732°, and 739° C., also the falling temperatures, and the standard hardening temperature of 760° C., were shown by a platinum resistance pyrometer and a Callendar Recorder. A length of 7.9 inches on the chart represented 50° on the platinum scale, equivalent, at the range of working, to about 63° C. on the air scale; thus each centigrade degree was represented by a length on the chart of fully $\frac{1}{8}$ inch, which allowed of very accurate temperature readings.

The thermocouple pyrometer and the resistance pyrometer were both protected by porcelain or quartz tubes enclosed in steel sheaths; and they were immersed, all the time of working, for about 10 inches of their length in the pyromelt. There must have been considerable lag in showing the temperature, but this was not important considering the slowness of the thermal movements.

Standardisation of Pyrometers and Degree of Accuracy Attained.

The normalising temperature, the hardening temperature, and the first furnace temperatures were maintained with moderate accuracy. In many cases the error did not exceed

2° or 3°, and it rarely reached 6° or 7° C. The second furnace temperatures, and the single heat temperatures, were usually correct within 1° or 2°, and probably the error rarely exceeded 2° or 3° C. A typical recorder sheet is reproduced in Fig. 29 (p. 213). In addition to the errors given above, the author's standard may have been incorrect by 2° or 3° C. in relation to the National Physical Laboratory. Bars B100 to B110 inclusive and blanks C108, C109, and C110 were, by mistake, only heated to 790° in the first furnace instead of to 800° C. Probably, however, this error made very little difference in the results, as no marked change occurs in the steel in the neighbourhood of 800° C. Bars B46 to B56 inclusive, and blanks C54, C55, and C56 were, by mistake, only heated to 740° instead of to 750° C.; and this error might have been serious as being near to the change Ac1.2.3. The results show, however, that the change was fully accomplished during the hour at 740°.

Method of Heating.

The test bars, cutter blanks, and test cutters were heated by immersion, for the periods of time shown, in the salt-bath, which had previously been raised to the required temperature. For single heats and first furnace heats, the pieces, including the cutters when they were being heated for the final hardening, were always cold when they entered the bath. In the case of two-furnace treatments, the pieces, after one hour's heating in the first furnace, were transferred as quickly as possible to the second furnace, which was already at the temperature shown. The time occupied in transferring from one furnace to the other would not be more than one or two seconds. Inasmuch as the second furnace was maintained at a lower temperature than the first, it would be strictly correct to speak of the pieces as being heated in the first furnace and cooled in the second. During the whole of the time that any of the pieces were in either furnace, whether for normalising, heat treatment, or hardening, the pyromelt was stirred every $2\frac{1}{2}$ minutes by two quick double strokes of the tray from the bottom of the bath to the top, right out of the liquid, and back again. No doubt a continuous stirring would have been better, but the uneven heating due to

the intermittency of the stirring could hardly exceed 2° or 3° in the worst cases.

The bars were transferred from the first furnace to the second by a hook in the wire already referred to (see Fig. 7, Plate VII.). At first nickel wires were used, which, however, were so brittle and weak at the high temperatures that they broke when the attempt was made to lift by them ; and on this account fifteen of the bars had to be transferred with cold tongs. Iron wire was then used, and no more trouble was experienced on this account. The bars which broke through the hole, with water-quenching from the heat treatment, were handled by cold tongs for the hardening. All the blanks were transferred from one furnace to the other with cold tongs. Some notes about the length of time required for heating in the salt-bath appear in Appendix II.

Normalising.

All the machined test bars and the cutter blanks, with the exception of B1, B2, C1, and C2, were normalised by heating to 825° C. in a salt-bath for one hour to allow the cementite to go into solution. At the end of the hour the bars and blanks were removed from the furnace and laid about 6 inches apart on wire netting raised about 3 inches from the ground, and allowed to cool in the air. No precaution was taken to protect them from draughts which may have varied considerably on different days.

Heat Treatment.

The heat treatments shown in Tables I.-V. (pp. 137-141) were given to the test bars and cutter blanks after they had been normalised without any intervening process. In the case of water-quenched pieces the temperature of the water and the method of quenching were the same as for the hardening of the test bars, as described in the next paragraph. The cooling in sand consisted of putting a bar or blank, direct from the furnace, into a tin of about 9 inches cube already half filled with fine dry sand at the temperature of the room, and then immediately the tin was filled up with sand and closed with a lid. Only one bar or blank was put into a tin at one time. The shortest time in the

sand was two hours for the bars and four hours for the blanks, and the pieces, though still hot, could then be removed by hand.

Hardening of Test Bars.

The test bars were heated, direct from the cold, in a salt-bath at a temperature of 760°C . for twenty minutes, and then quenched in water. As explained in a previous paragraph on the method of heating, some of the bars were handled by a hook in a wire loop, and some by tongs ; but in all cases they were plunged vertically into the water, so that the higher end was about 6 inches below the surface. They were then moved sideways, to and fro, for about ten seconds. The horizontal movement in each direction was about 18 inches, and occupied about one second. At the end of ten seconds (five double strokes) the stirring ceased, but the bars remained in the water for another twenty seconds with little motion. They were lifted out of the water in half a minute from the time of entering it. The temperature of the water was rarely outside the limits of 10° to 13°C . The extremes were 8° and 14°C . This process is referred to, in the following pages, as the standard hardening.

Hardening of Test Cutters.

The test cutters were heated, for the standard hardening, direct from the cold, in a salt-bath at 760°C . for fifteen minutes. They were then removed with a cold hook and quickly placed in a wire basket, with the hole vertical and the thick end downwards. The basket was plunged into water so that the top of the cutter was about 4 or 5 inches below the surface, and it was then moved sideways, to and fro, for about ten seconds. The horizontal motion (as in the case of the bars) was about 18 inches, and occupied about one second in each direction. After ten seconds (five double strokes) the cutter was still warm to the hand, and was allowed to remain in the water for another twenty seconds with very little motion. It was removed from the water in about half a minute from the time of entering it. The temperature of the water was the same as given in the previous paragraph for the bars. Many of the cutters cracked before removal from the

water, some of them breaking in two around the recess. In most cases the teeth continued to click for an hour or more, and occasionally for days. A few cutters jumped in two, a quarter of an hour or more after they had been hardened.

Etching.

Many of the test bars were subjected to rather prolonged heat treatments which, in some cases, extended to thirteen hours, and in a few cases to sixteen or seventeen hours; also many bars, though heated for shorter periods of time, underwent as part of their treatment an hour at such high temperatures as 850° or 900° C. In consequence of prolonged heating and high temperature, some of the bars were slightly etched on the surface, as indicated in Table VII., and this etching must have affected the length measurements. About a dozen bars were etched more than the others, and of these B217 was perhaps the worst. This bar was found to be two or three thousandths of an inch big in thickness when measured over the tops of the prominences, and three or four thousandths small when measured at the bottom, after the prominences had been carefully ground away.

Hardening Cracks in Test Bars.

After the heat treatment all the bars were boiled for a short time in water. Those that had been water-quenched were then dipped into oil, after which they were sand-blasted and examined for cracks, the appearance of oil on the sand-blasted surface making their detection easy. In some cases the end was broken right off, or was just holding on to the bar by the four corners; and there were all degrees between such bad breakages and the occurrence of a slight crack visible in one place only; also there were probably some cracks which were never detected. The sand-blast method of examination for cracks was again applied after the standard hardening. In Table VII. an asterisk in the column for heat treatment or for hardening, as the case may be, shows which bars were cracked; and the probability of the measurement being affected must be kept in mind. No indication has been given in the table of the extent of the cracks, except that in the case of bad cracks the length measurement

has of course been omitted. The cracking of bars in relation to the defectiveness of cutters is dealt with in Appendix VIII.

Change in Length of Test Bars.

Before and after the normalising, heat treatment, and standard hardening, the test bars were placed in a fixing made for the purpose; and the length was measured with a micrometer, provided with a spring ratchet stop, by which the estimation of figures for the ten-thousandth of an inch could be made with moderate accuracy. Any lengthening or shortening is shown in Table VII. as plus (+) or minus (—), to the nearest half-thousandth. Further information about the measurements, and about progressive changes in length, is given in Appendix III.

Hardness Tests.

Following the heat treatment, the bars were smooth ground on one broad and one narrow side for about an inch from the end, as shown in Fig. 6. The amount removed was $\frac{1}{64}$ inch, and the grinding was done under a flood of water. After the grinding the Brinell and Shore tests were applied to the broad surface. Subsequently, after the standard hardening, the portion of the narrow side which had been previously ground was slightly polished with emery cloth, and the hardness tests were again applied. The polishing after hardening was considered sufficient, instead of grinding, because the standard hardening was the same throughout, and any effect on the surface of the steel would be about the same for all; so that the comparative value of the results would not be affected. After the heat treatment the blanks were smooth ground on one end about half way across, and the hardness tests were applied in a similar position throughout.

Bending Tests.

The bending tests were carried out with great care, at the Brown-Firth Research Laboratories, on supports $5\frac{1}{4}$ inches apart. A full account of this work is given in Appendix IV.

The Machining of the Cutter Blanks.

After the heat treatment, followed by grinding and hardness testing, the cutter blanks were machined up into test cutters. A

B19	"	"	"	"	"	12	"	"	"	...	-0.0095	...	514	85	over	91	173.1	120.8	3.80	2.21	81.8
B19a	"	"	"	"	760°	20	"	"	"	...	-0.0060	-0.0115	418	62	700	91	173.1	120.8	3.80	2.21	81.8
B20	"	"	"	"	"	16	"	"	"	...	-0.0080	...	321	50	over	93	152.4	118.8	3.43	2.57	59.6
B21a	"	"	"	"	760°	20	"	sand	"	...	-0.0010	-0.0020*	217	31	700	93	152.4	118.8	3.43	2.57	59.6
B22	"	"	"	"	"	4	"	"	"	...	-0.0015	...	217	35	over	94	174.7	116.6	3.59	2.16	74.3
B22a	"	"	"	"	760°	20	"	"	"	...	-0.0035	-0.0030	223	32	700	94	174.7	116.6	3.59	2.16	74.3
B24a	"	"	"	"	"	12	"	"	"	...	-0.0035	-0.0045*	207	30	"	94	168.6	118.8	4.02	2.57	80.0
B25	"	"	"	"	"	16	"	"	"	...	-0.0040	...	217	35	over	94	168.6	118.8	4.02	2.57	80.0
B26	825°	1	...	725°	1	water	760°	20	"	...	-0.0075	...	241	40	over	94	148.1	133.8	3.31	2.92	55.3
B27	"	"	"	"	"	4	"	"	"	...	-0.0075	-0.0010	217	34	"	95	184.5	114.3	3.95	2.12	87.7
B28	"	"	"	"	"	8	"	"	"	...	-0.0070	-0.0030	207	34	"	95	147.0	121.5	3.41	2.64	59.7
B29	"	"	"	"	"	12	"	"	"	...	-0.0065	nil	207	34	"	95	143.7	108.4	3.19	2.25	50.5
B30	"	"	"	"	"	16	"	"	"	...	-0.0060	-0.0005	201	33	555†	91	166.6	122.5	3.95	2.61	70.8
B31	"	"	"	"	"	1	sand	"	"	...	-0.0005	-0.0015*	223	34	over	93	136.9	127.6	3.03	2.26	46.4
B32	"	"	"	"	"	4	"	"	"	...	-0.0015	-0.0020	207	29	"	94	179.6	147.0	4.10	2.98	89.0
B35	"	"	"	"	"	16	"	"	"	...	-0.0015	-0.0010	197	32	"	93	147.0	111.0	3.78	2.48	67.6
B36	825°	1	...	718°	1	water	760°	20	"	...	-0.0070	-0.0030	228	38	"	93	151.9	111.0	3.24	2.26	56.3
B37	"	"	"	"	"	4	"	"	"	...	-0.0080	-0.0025	217	35	"	92	168.2	115.9	3.48	2.13	69.5
B38	"	"	"	"	"	12	"	"	"	...	-0.0060	-0.0005	207	34	"	97	133.2	124.1	2.93	2.66	44.2
B39	"	"	"	"	"	16	"	"	"	...	-0.0060	-0.0005	207	34	444†	93	130.6	117.6	2.80	2.51	40.5
B40	"	"	"	"	"	1	sand	"	"	...	-0.0005	-0.0045	217	35	over	91	150.2	127.4	3.13	2.58	53.3
B41	"	"	"	"	"	4	"	"	"	...	-0.0015	-0.0015	217	34	"	92	182.9	117.6	4.26	2.31	96.4
B43	"	"	"	"	"	16	"	"	"	...	-0.0025	nil	197	32	444†	90	146.0	117.6	3.23	2.45	54.7
B44	825°	1	750°	1	...	...	water	760°	20	...	-0.0010*	...	over	73	700	92	140.0	125.7	3.20	2.89	49.6

* These bars were cracked under the process indicated.

† These bars were etched on the surface. Figures given for change in length may be too high but not too low.

† These cars were tested on the surface. Figures given for change in length may be too low but are not likely to be too high. These values apply to a point $\frac{1}{8}$ inch from the ends of the bars. On re-test nearer to the ends of bars the values obtained were in each case over 700, which figure has been adopted.

TABLE VII.—(continued).

Refer- ence, Number.	Normalising.			Heat Treatment.				Hardening.		Change in Length.		Hardness.				Bending Tests.				Energy, Ft.-Lbs.	
	Temp. °C.	Time, Hour.	Cooling.	First Furnace.		Second Furnace.		Temp. °C.	Time, Mins.	Due to Heat Treatment, Inch.	Due to Hardening, Inch.	Brinell.	Shore.	After Heat Treatment.	Brinell.	Shore.	Stress.		Deflection.		
				Temp. °C.	Time, Hour.	Temp. °C.	Time, Hour.										Max. Tons per Sq. In.	E. L. Tons per Sq. In.	Max. Milli- metres.		E. L. Milli- metres.
B45	825°	1		750°	1			760°	20	-0.0030	-0.0030	228	33	700	91	153.5	122.5	3.23	2.27	60.2	
B46	825	1	sand	732°	1	...	...	"	"	-0.0025	-0.0155	652	67	"	91	147.0	140.4	3.05	2.90	49.6
B47	"	"	water	"	"	1 1/4	1 1/4	"	"	-0.0010	-0.0140*	627	80	"	93	161.8	134.4	3.86	3.07	71.4	
B48	"	"	"	"	"	1 1/2	1 1/2	"	"	+0.0005*	...	700	82	"	93	148.1	135.6	3.44	3.03	58.4	
B49	"	"	"	"	"	1 1/2	1 1/2	"	"	-0.0020	-0.0165	652	80	"	92	150.2	130.6	3.12	2.65	53.0	
B50	"	"	"	"	"	2	2	"	"	-0.0015	-0.0140*	700	84	"	93	187.8	140.4	4.17	2.80	93.8	
B51	"	"	"	"	"	4	4	"	"	-0.0030	-0.0150	"	87	"	94	174.7	137.2	3.80	2.83	76.5	
B52	"	"	"	"	"	8	8	"	"	-0.0080	-0.0150	600	85	"	91	161.7	142.1	3.30	2.75	61.7	
B53	"	"	"	"	"	12	12	"	"	-0.0085	-0.0140*	652	80	"	90	164.9	150.2	3.08	2.75	57.3	
B54	"	"	sand	"	"	1	1	"	"	-0.0030	-0.0030*	228	35	"	92	162.7	135.0	4.08	3.18	77.1	
B55	"	"	"	"	"	4	4	"	"	-0.0040	-0.0070	228	35	"	92	182.9	119.2	3.93	2.33	84.6	
B56	"	"	"	"	"	12	12	"	"	-0.0045	-0.0100	228	37	"	93	156.8	120.8	3.25	2.30	60.0	
B57	825°	1	water	725°	1	1 1/4	1 1/4	760°	20	-0.0025	-0.0130	555	80	"	94	155.1	127.4	3.17	2.47	56.9	
B58	"	"	"	"	"	1 1/4	1 1/4	"	"	-0.0010	-0.0125*	652	85	"	92	165.5	156.8	4.09	3.88	75.0	
B59	"	"	"	"	"	1 1/2	1 1/2	"	"	-0.0020	-0.0155	700	88	"	91	150.2	137.2	2.90	2.62	48.7	
B60	"	"	"	"	"	1	1	"	"	-0.0030	-0.0150	600	79	"	91	168.2	133.9	3.37	2.52	65.9	
B61	"	"	"	"	"	2	2	"	"	-0.0045	-0.0130	600	79	"	92	179.6	148.6	3.56	2.74	75.1	
B62	"	"	"	"	"	4	4	"	"	-0.0060	-0.0145	600	80	"	92	182.9	147.0	3.75	2.72	82.3	
B63	"	"	"	"	"	8	8	"	"	-0.0085	-0.0115	495	77	"	92	148.6	134.3	3.13	2.32	51.5	
B64	"	"	"	"	"	12	12	"	"	-0.0090	-0.0110	512	80	"	92	163.3	119.2	3.70	2.35	73.7	
B65	"	"	"	"	"	16	16	"	"	-0.0100	-0.0020	207	34	"	96	163.3	119.2	3.80	2.50	73.7	

B66	"	"	"	"	"	1	sand	"	"	-0.0030	-0.0030	235	35	"	92	160.0	140.4	3.07	2.60	56.1
B67	"	"	"	"	"	1	"	"	"	-0.0035	-0.0055	228	35	"	90	161.7	133.9	3.03	2.46	58.4
B68	"	"	"	"	"	4	"	"	"	-0.0035	-0.0030	217	32	"	92	132.3	119.2	3.50	2.37	62.7
B69	"	"	"	"	"	12	"	"	"	-0.0035	-0.0075	223	32	"	92	174.7	130.6	3.93	2.67	81.5
B70	"	"	"	"	"	16	"	"	"	-0.0030	+0.0005	207	33	"	97	171.5	107.8	4.16	2.36	83.8
B71	825°	1	750°	1	718°	$\frac{1}{8}$	water	760°	20	-0.0025	-0.0100	512	79	"	93	153.5	124.1	3.06	2.41	53.0
B72	"	"	"	"	"	$\frac{1}{4}$	"	"	"	-0.0005	-0.0040	332	50	"	93	163.3	114.3	3.36	2.24	62.8
B73	"	"	"	"	"	$\frac{1}{2}$	"	"	"	-0.0040	***	241	37	"	93	150.6	142.5	3.66	3.47	61.0
B74	"	"	"	"	"	1	"	"	"	-0.0070	-0.0010	207	31	"	93	160.0	133.9	3.28	2.63	60.2
B75	"	"	"	"	"	2	"	"	"	-0.0080	+0.0005	207	30	"	94	179.6	140.4	3.85	2.85	75.5
B76	"	"	"	"	"	4	"	"	"	-0.0085	+0.0010	196	31	"	92	178.0	135.5	3.85	2.75	79.4
B77	"	"	"	"	"	8	"	"	"	-0.0095	+0.0010	196	31	"	93	163.3	117.6	3.48	2.35	65.7
B78	"	"	"	"	"	12	"	"	"	-0.0120	-0.0010	179	30	"	95	133.9	127.4	2.57	2.45	38.1
B79	"	"	"	"	"	$\frac{1}{4}$	sand	"	"	-0.0030	-0.0010	207	30	"	94	158.4	122.5	3.44	2.49	63.3
B80	"	"	"	"	"	4	"	"	"	-0.0020	-0.0010	192	29	"	93	163.3	120.8	3.41	2.31	65.5
B81	"	"	"	"	"	4	"	"	"	-0.0020	+0.0010	187	28	"	92	174.7	111.0	4.30	2.20	96.6
B82	"	"	"	"	"	12	"	"	"	-0.0055	-0.0005	170	26	"	92	182.9	130.6	4.01	2.51	88.9
B83	825°	1	750°	1	706°	$\frac{1}{4}$	water	760°	20	-0.0065	-0.0025	207	35	"	94	133.1	110.4	3.11	2.47	47.4
B84	"	"	"	"	"	$\frac{1}{2}$	"	"	"	-0.0070	-0.0030	207	32	"	91	151.9	143.7	3.36	2.20	39.7
B85	"	"	"	"	"	1	"	"	"	-0.0075	nil	207	33	"	93	147.0	130.6	3.12	2.74	52.6
B86	"	"	"	"	"	2	"	"	"	-0.0085	-0.0005	212	32	"	92	161.7	127.4	3.66	2.72	68.6
B87	"	"	"	"	"	$\frac{1}{4}$	sand	"	"	-0.0015	-0.0010	196	29	"	94	143.7	113.7	3.33	2.45	55.8
B88	"	"	"	"	"	1	"	"	"	-0.0020	-0.0015	196	28	"	92	148.6	134.6	3.47	3.03	59.0
B89	"	"	"	"	"	2	"	"	"	-0.0020	-0.0005	196	27	"	91	106.1	99.3	2.28	2.12	26.8
B90	825°	1	750°	1	740°	2	water	760°	20	-0.0035	-0.0010*	375	49	"	93	159.9	132.9	3.94	3.14	71.9
B91	"	"	"	"	718°	8	"	"	"	-0.0085	-0.0020	228	38	"	93	169.8	124.1	3.67	2.43	73.7
B92	"	"	"	"	"	2	sand	"	"	-0.0030	-0.0010	217	33	"	95	166.5	130.6	3.37	2.45	72.2
B93	"	"	"	"	"	8	"	"	"	-0.0030	-0.0005	187	27	"	94	168.2	111.0	3.70	2.21	59.1
B94	825°	1	750°	1	740°	3	water	760°	20	-0.0075	-0.0020	202	31	"	94	182.9	130.6	3.90	2.38	87.7

* These bars were cracked under the process indicated. Figures given for change in length may be too high but not too low.

TABLE VII.—(continued).

Refer- ence Number.	Heat Treatment.				Hardening, Quenching in Water.		Change in Length.		Hardness.				Bending Tests.							
	Normalising. Cooling in Air.		First Furnace.		Second Furnace.		Cooling.	Due to Heat Treatment. Inch.		Due to Hardening, Inch.		After Heat Treatment.		After Hardening.		Stress.		Deflection.		Energy. Ft.-Lbs.
	Temp. °C.	Time. Hour.	Temp. °C.	Time. Hour.	Temp. °C.	Time. Hour.		Temp. °C.	Time. Mins.	Britnell.	Shore.	Britnell.	Shore.	Max. Tons per Sq. In.	E. L. Tons per Sq. In.	Max. Milli- metres.	E. L. Milli- metres.			
B95	825°	1	750°	1	740° to 706°	12	water	760°	20	-0.0100	-0.0015	196	33	over 700	94	166.6	123.1	3.18	2.13	62.7
B96	"	"	"	"	"	3	sand	"	"	-0.0025	-0.0010	187	28	"	93	138.8	117.6	2.82	2.31	44.6
B97	"	"	"	"	"	12	"	"	"	-0.0035	-0.0030	183	28	"	92	174.7	120.8	3.72	2.27	74.8
B98	825°	1	800°	1	...	...	water	760°	20	-0.0100*	...	700	77	"	92	146.2	122.9	3.64	2.98	57.3
B99	"	"	"	"	...	...	sand	"	"	-0.0010	-0.0005*	248	36	"	94	126.9	110.1	3.09	2.68	41.3
B100	825°	1	800°	1	732°	1	water	760°	20	-0.0015*	...	600	76	"	93	151.2	123.2	3.59	2.82	61.9
B101	"	"	"	"	"	"	"	"	"	-0.0015*	...	555	75	"	93	140.0	128.8	3.21	2.92	49.7
B102	"	"	"	"	"	1	"	"	"	-0.0005*	...	700	78	"	93	118.2	112.0	2.67	2.52	35.0
B103	"	"	"	"	"	1	"	"	"	-0.0035	-0.0145	"	77	"	93	156.8	132.3	3.28	2.68	58.5
B104	"	"	"	"	"	2	"	"	"	-0.0035	-0.0145	"	80	"	93	163.3	127.4	3.40	2.50	64.2
B105	"	"	"	"	"	4	"	"	"	-0.0065	-0.0145	555	79	"	93	163.3	124.1	3.29	2.39	61.5
B106	"	"	"	"	"	8	"	"	"	-0.0055	-0.0090	477	75	"	92	140.4	111.0	3.18	2.33	52.3
B107	"	"	"	"	"	12	"	"	"	-0.0085	-0.0090*	512	71	"	93	122.0	110.8	2.82	2.55	38.1
B108	"	"	"	"	"	1	sand	"	"	-0.0020	-0.0050	228	30	"	92	150.2	112.7	3.05	2.10	53.9
B109	"	"	"	"	"	4	"	"	"	-0.0030	-0.0045	235	35	"	92	129.0	117.6	2.72	2.47	38.9
B110	"	"	"	"	"	12	"	"	"	-0.0025	-0.0065	228	35	"	94	133.9	111.0	2.60	2.00	40.8
B111	825°	1	800°	1	725°	1	water	760°	20	-0.0015*	...	512	73	"	90	149.3	141.9	3.42	3.25	56.5
B112	"	"	"	"	"	1	"	"	"	-0.0035	-0.0140	477	54	"	93	114.3	94.7	2.46	1.96	32.1
B113	"	"	"	"	"	1	"	"	"	-0.0030	-0.0150	700	78	"	93	125.7	117.6	2.51	2.35	34.9

TABLE VII.—(continued).

Reference Number.	Normalising. Cooling in Air.				Heat Treatment.				Hardening. Quenching in Water.				Change in Length.		Hardness.				Bending Tests.				Energy. Ft.-Lbs.
	Temp. C.	Time. Hour.	First Furnace.		Second Furnace.		Cooling.	Hardening. Quenching in Water.		Due to Heat Treatment. Inch.	Due to Hardening. Inch.	Brinell.	Shore.	After Heat Treatment.	After Hardening.		Stress. Max. Tons per Sq. In.	E. L. Tons per Sq. In.	Deflection.				
			Temp. C.	Time. Hour.	Temp. C.	Time. Hour.		Brinell.	Shore.						Max. Tons per Sq. In.	E. L. Tons per Sq. In.			Max. Milli-metres.	E. L. Milli-metres.			
B142	825°	1	800°	1	706°	1	sand	760°	20	-0.0010	-0.0030	196	27	477 [†] over 700	90	133.9	111.7	3.03	2.38	47.1			
B143	"	"	"	"	"	"	"	"	"	-0.0015	+0.0035*	187	29	700	92	155.1	142.1	3.75	3.27	67.2			
B144	825°	1	800°	1	740° to 718°	1	water	760°	20	...*	...	683	72	"	92	146.8	135.9	3.47	3.10	58.2			
B145	"	"	"	"	"	"	"	"	"	-0.0030	-0.0065*	444	60	"	92	166.6	140.4	3.50	2.80	64.8			
B146	"	"	"	"	"	"	"	"	"	-0.0050	-0.0085	460	60	"	93	140.4	124.1	2.84	2.43	41.9			
B147	"	"	"	"	"	"	"	"	"	-0.0045	nil	241	32	"	92	106.1	98.0	2.32	2.13	27.3			
B148	"	"	"	"	"	"	1 sand	"	"	-0.0005	-0.0015*	228	32	"	92	100.8	94.6	2.36	2.22	26.5			
B149	"	"	"	"	"	"	2 "	"	"	-0.0010	...*	217	31	"	92	141.2	133.8	3.42	3.14	54.9			
B150	"	"	"	"	"	"	4 "	"	"	-0.0010	-0.0015	187	27	"	91	137.2	130.6	2.89	2.74	43.9			
B151	"	"	"	"	"	"	8 "	"	"	-0.0035 [†]	+0.0010	207	29	"	91	135.2	127.4	2.90	2.65	44.6			
B152	825°	1	800°	1	740° to 706°	3	water	760°	20	-0.0070	...*	196	30	"	93	136.9	127.0	2.88	2.68	43.6			
B153	"	"	"	"	"	12	"	"	"	-0.0075	-0.0025	187	30	"	91	160.0	117.2	3.18	2.08	64.4			
B154	"	"	"	"	"	3	sand	"	"	-0.0015	...*	187	26	"	93	124.4	110.8	3.00	2.64	41.3			
B155	"	"	"	"	"	12	"	"	"	-0.0025 [†]	-0.0005	170	27	"	94	163.3	117.6	3.64	2.44	69.1			
B156	825°	1	850°	1	...	...	water	760°	20	-0.0145	-0.0130*	652	78	"	90	115.7	105.8	2.80	2.41	37.8	
B157	"	"	"	"	...	...	sand	"	"	+0.0010	-0.0030*	269	38	"	93	118.2	103.9	2.82	2.37	38.4	
B158	825°	1	850°	1	732°	½	water	760°	20	nil	-0.0150*	over 700	85	"	92	141.8	120.0	3.46	2.67	58.7			

TABLE VII.—(continued).

Refer- ence Number.	Normalising: Cooling in Air.				Heat Treatment.				Hardening. Quenching in Water.		Change in Length.		Hardness.		Bending Tests.				
	Temp. C.	Time. Hour.	First Furnace.		Second Furnace.		Cooling.	Temp. C.	Time. Mins.	Due to Heat Treatment. Inch.	Due to Hardening. Inch.	After Heat Treatment.		After Hardening.		Stress.		Deflection.	Energy, Ft.-lbs.
			Temp. C.	Time. Hour.	Temp. C.	Time. Hour.						Brinell.	Shore.	Brinell.	Shore.	Max. Tons per Sq. In.	E. L. Tons per Sq. In.		
B186	825°	1	850°	1	718°	4	water	760°	20	-0.0075	nil	196	32	165.3	121.5	3.59	2.47	68.8	
B187	"	"	"	"	"	8	"	"	"	-0.0085	-0.0010	196	31	150.9	124.1	3.30	2.55	57.9	
B188	"	"	"	"	"	12	"	"	"	-0.0105	nil	196	30	179.6	137.2	3.97	2.90	81.6	
B189	"	"	"	"	"	1	sand	"	"	-0.0005	...	241	32	138.5	107.8	3.05	2.33	47.4	
B190	"	"	"	"	"	1	"	"	"	-0.0010	-0.0015	196	29	145.7	107.8	3.20	2.25	53.5	
B191	"	"	"	"	"	4	"	"	"	-0.0025	+0.0015	179	26	180.9	130.6	4.09	2.76	85.8	
B192	"	"	"	"	"	12	"	"	"	-0.0040†	-0.0005	187	28	162.0	118.2	3.83	2.43	75.2	
B193	825°	1	850°	1	706°	1	water	760°	20	+0.0020	-0.0025*	364	47	100.8	94.6	2.15	2.01	23.9	
B194	"	"	"	"	"	1	"	"	"	-0.0055	...	217	35	151.2	143.1	3.18	3.01	53.3	
B195	"	"	"	"	"	1	"	"	"	-0.0060	...	217	35	149.3	130.7	3.40	2.79	59.1	
B196	"	"	"	"	"	2	"	"	"	-0.0065	...	207	31	135.9	107.1	3.08	2.31	48.1	
B197	"	"	"	"	"	1	sand	"	"	+0.0005	-0.0030	202	29	135.2	123.5	3.25	2.85	50.4	
B198	"	"	"	"	"	1	"	"	"	nil	-0.0030	207	30	162.6	114.3	3.90	2.50	74.6	
B199	"	"	"	"	"	2	"	"	"	-0.0015	+0.0010	192	28	155.1	122.5	3.69	2.70	67.0	
B200	825°	1	850°	1	740°	2	water	760°	20	+0.0040	...	460	56	102.7	94.6	2.29	2.10	26.0	
B201	"	"	"	"	"	8	"	"	"	-0.0100	-0.0015	207	32	156.1	109.7	3.55	2.31	56.4	
B202	"	"	"	"	"	2	sand	"	"	-0.0005	+0.0020*	255	36	133.9	120.8	2.98	2.63	45.1	
B203	"	"	"	"	"	8	"	"	"	-0.0050	+0.0005	196	27	168.9	124.8	3.93	2.75	76.4	
B204	825°	1	850°	1	740°	3	water	760°	20	-0.0080	+0.0055	207	35	152.8	122.8	3.22	2.50	56.0	

B205	"	"	"	12	"	"	"	"	-0.0080	+0.0005	187	30	93	117.6	111.0	2.67	2.52	34.7
B206	"	"	"	3	sand	"	"	"	-0.0020	+0.0030*	196	27	92	114.3	99.3	2.40	2.07	30.4
B207	"	"	"	12	"	"	"	"	-0.0045	-0.0045	179	27	96	166.6	112.7	4.40	2.28	96.3
B208	825°	1	900°	"	water	760°	20	"	-0.00258	...	652	71	90	...	...	...	...	...
B209	"	"	"	...	sand	"	"	"	+0.0035	-0.0065	302	41	90	127.4	114.3	2.77	2.46	39.4
B210	825°	1	900°	1	water	760°	20	"	+0.0145	-0.0140*	683	81	91	134.7	126.3	2.92	2.71	43.7
B211	"	"	"	1	"	"	"	"	+0.0030*	...	over 700	84	92	134.4	120.1	3.17	2.73	48.7
B212	"	"	"	1	"	"	"	"	+0.0020*	...	652	79	91	135.6	127.5	3.09	2.92	46.3
B213	"	"	"	1	"	"	"	"	+0.0030*	...	652	80	91	128.8	112.9	2.88	2.51	41.2
B214	"	"	"	2	"	"	"	"	+0.0030†	...*	652	81	90	147.5	135.6	3.20	2.86	53.4
B215	"	"	"	4	"	"	"	"	+0.0080†	-0.0120	652	80	93	127.4	120.8	2.52	2.42	35.5
B216	"	"	"	8	"	"	"	"	+0.0015†	-0.0120*	627	77	90	137.5	126.9	3.10	2.64	47.0
B217	"	"	"	12	"	"	"	"	-0.0065†	-0.0105*	627	78	92	125.1	112.0	2.78	2.48	36.6
B218	"	"	"	1	sand	"	"	"	+0.0010	-0.0010*	269	37	600†	132.5	125.6	2.85	2.71	42.0
B219	"	"	"	4	"	"	"	"	nil	...	262	37	over 700	150.2	133.1	3.37	2.88	58.2
B220	"	"	"	12	"	"	"	"	-0.0030†	-0.0015*	241	35	93	150.0	141.9	3.27	3.09	54.4
B221	825°	1	900°	1	water	760°	20	"	+0.0005*	...	over 700	81	90	146.2	134.4	3.17	2.74	62.4
B222	"	"	"	1	"	"	"	"	+0.0160	...	683	80	90	146.2	130.7	3.42	2.86	58.4
B223	"	"	"	1	"	"	"	"	+0.0160	-0.0015*	652	77	91	137.5	129.4	3.05	2.85	46.5
B224	"	"	"	1	"	"	"	"	+0.0040	...	652	68	92	118.8	110.8	2.64	2.48	35.6
B225	"	"	"	2	"	"	"	"	+0.0030	...	652	70	90	103.5	95.8	2.33	2.15	26.6
B226	"	"	"	4	"	"	"	"	+0.0130†	...	652	68	90	104.5	97.4	2.33	2.15	26.6
B227	"	"	"	8	"	"	"	"	+0.0040†	-0.0050	387	52	90	132.0	101.2	2.89	2.13	43.5
B228	"	"	"	12	"	"	"	"	-0.0035†	-0.0030	277	41	90	114.0	98.0	2.50	2.15	31.6
B229	"	"	"	1	sand	"	"	"	+0.0020	-0.0030*	277	42	90	133.6	116.6	2.91	2.50	43.6
B230	"	"	"	1	"	"	"	"	+0.0005	...	286	38	90	140.6	128.8	3.20	2.92	49.8

* These bars were cracked under the process indicated.

† These bars were etched on the surface. Figures given for change in length may be too low but are not likely to be too high.

† These values apply to a point $\frac{1}{8}$ inch from the ends of the bars. On re-test nearer to the ends of bars the values obtained were in each case over 700, which figure has been adopted.

§ Cracked longitudinally almost in two pieces; also two or three other cracks.

|| Slight longitudinal crack.

TABLE VII.—(continued).

Refer- ence Number.	Normalising.			Heat Treatment.				Hardening.		Change in Length.		Hardness.		Bending Tests.						
	Temp. °C.	Time. Hour.	Temp. °C.	First Furnace.	Second Furnace.		Cooling.	Temp. °C.	Time. Mins.	Due to Heat Treatment. Inch.	Due to Hardening. Inch.	After Heat Treatment.		After Hardening.	Stress.		Deflection.	Energy. Ft.-Lbs.		
					Temp. °C.	Time. Hour.						Brinell.	Shore.		Max. Tons per Sq. In.	E. L. Tons per Sq. In.				
																			Brinell.	Shore.
B231	825°	1	900°	1	725°	4	sand	760°	20	nil	-0.0010	255	over	92	132.3	105.2	2.97	2.25	45.1	
B232	"	"	"	"	"	12	"	"	"	-0.0035†	+0.0030	207	31	"	93	151.5	104.5	3.50	2.28	60.8
B233	825°	1	900°	1	718°	1	water	760°	20	+0.0025	...*	652	81	"	93	133.8	126.6	2.86	2.70	42.4
B234	"	"	"	"	"	1	"	"	"	+0.0160	-0.0110*	700	81	"	94	126.7	111.0	2.64	2.32	37.1
B235	"	"	"	"	"	1	"	"	"	+0.0050	-0.0060	418	66	"	93	119.5	105.8	2.91	2.43	40.4
B236	"	"	"	"	"	1	"	"	"	+0.0065	nil*	321	43	"	90	121.5	113.0	2.58	2.40	34.7
B237	"	"	"	"	"	2	"	"	"	-0.0015	...*	241	38	"	90	126.3	109.5	2.64	2.28	36.9
B238	"	"	"	"	"	2	"	"	"	-0.0060	...*	223	35	"	90	147.8	130.7	3.54	3.04	56.5
B239	"	"	"	"	"	8	"	"	"	-0.0060	nil	212	36	"	91	134.6	120.8	3.10	2.63	48.5
B240	"	"	"	"	"	12	"	"	"	-0.0070†	-0.0005	212	34	"	94	145.0	118.2	3.27	2.46	55.8
B241	"	"	"	"	"	16	"	"	"	-0.0095	+0.0005	207	35	"	95	135.5	111.0	3.35	2.45	54.9
B242	"	"	"	"	"	1	sand	"	"	+0.0010	.....*	241	41	"	93	122.8	113.0	2.74	2.53	37.3
B243	"	"	"	"	"	1	"	"	"	nil	...*	228	33	"	92	104.8	97.1	2.17	2.02	25.2
B244	"	"	"	"	"	4	"	"	"	-0.0010	-0.0010	212	33	"	92	133.9	116.0	3.17	2.61	49.4
B245	"	"	"	"	"	12	"	"	"	-0.0005†	-0.0020	207	31	"	96	115.0	99.9	2.45	2.14	31.2
B246	"	"	"	"	"	16	"	"	"	-0.0055	-0.0020	197	31	"	92	137.2	124.1	3.37	2.84	54.4
B247	825°	1	900°	1	706°	1	water	760°	20	+0.0085	-0.0040	512	over	94	151.9	124.1	3.25	2.52	56.9	
B248	"	"	"	"	"	1	"	"	"	-0.0010	+0.0010	248	38	"	93	147.0	130.6	3.13	2.78	50.9
B249	"	"	"	"	"	1	"	"	"	-0.0035	...*	248	37	"	90	155.1	124.1	3.44	2.58	62.2
B250	"	"	"	"	"	2	"	"	"	-0.0050	-0.0005	228	37	"	90	155.1	122.5	3.21	2.41	57.3
B251	"	"	"	"	"	1	sand	"	"	+0.0015	+0.0015	228	33	"	92	148.6	127.4	2.95	2.43	50.1
B252	"	"	"	"	"	1	"	"	"	+0.0005	-0.0045	228	32	"	91	161.7	119.2	3.45	2.28	66.9

"machining-number" was given to each blank according to the ease or difficulty of cutting, No. 1 being given to the easiest and No. 6 to the most difficult. Details of the machining and of the machining-numbers are given in Appendix V.

Defectiveness of Test Cutters.

The method used for detecting hardening cracks in test bars was also employed to examine the test cutters. The group shown in Fig. 2, Plate VI., was photographed after the cutters had been oiled and sand-blasted to show up the cracks. In order to provide some standard of comparison one, two, or three marks of defectiveness were assigned for every crack or break, according to its degree of badness. A cutter which broke in two around the recess would be given, therefore, three marks for each of the 16 teeth, amounting to 48 marks, and there might be further marks for cracks at either end (see Fig. 8, Plate VIII.). A cutter which had a minute crack on each of five teeth would have a defectiveness of five assigned to it, although there might not be a fault capable of detection by ordinary examination; but a cutter with a single tooth badly cracked at one end, and no other fault, would have a defectiveness of only three. From a commercial point of view, the cutter with a defectiveness of five would be entirely satisfactory, and the other, with only three marks against it, would be unsaleable; but this aspect is not taken into account, because, so far as possible, the classification is made solely with respect to the liability to crack, and regardless of other considerations. Comparisons by means of the defectiveness figures must not be pushed too far; for example, some test cutters broke in two immediately on hardening and scarcely cracked again, the defectiveness being little more than 48; whilst other cutters kept cracking at both ends for a time, and then broke in two, after which the end-cracking ceased. In the latter case the defectiveness might be 60 or 70 or more; and yet if these cutters had broken in two without delay, many of the end cracks would probably not have occurred. A chance determining cause might hasten the break around the recess, thus easing some of the stresses set up by hardening.

PART III.

CONSIDERATION OF RESULTS.

General Explanation.

The results obtained from the complete series of test bars are shown in Table VII., and the results from the test cutters in Table VIII. In considering the results, it is essential continually to keep clearly in mind the different processes involved. Frequent references to the various treatments which were given must not be allowed to obscure the fact that all the test bars, with eight exceptions, and all the test cutters, were finally hardened by one standard process, and the differences in behaviour on hardening arose from the previous heat treatment. Note should be made of the following difference between the treatment of the bars and cutters. The bars underwent the various heat treatments specified, after which they were given the standard hardening; but in the case of the cutters, the various heat treatments were applied to the cutter blanks, which were afterwards machined up into cutters. The only treatment given to the machined cutters was the standard hardening, and there was no cutter which received any treatment different from that given to all the others.

When heat-treated bars are spoken of it is necessary carefully to distinguish between water-quenched and sand-cooled bars, and this distinction must still be remembered when hardened bars are under consideration; for interest centres about the previous treatment, in which the manner of cooling was an essential factor. In the case of cutter blanks the heat treatment was always followed by sand-cooling.

It is important that the bases of various comparisons which are suggested should in each case be clearly understood. Comparisons are made between various bars (or between bars, blanks, or cutters) at different stages of their treatment, or between pieces which received similar treatments differing only in certain particulars; for example, it is desired to examine a relationship between (a) the defectiveness of hardened cutters, and (b) the physical condition of the corresponding water-quenched

C54	"	"	"	732°	1	212	37	4	"	"	24	48	0	72
C55	"	"	"	"	4	207	33	4	"	"	37	48	3	88
C56	"	"	"	"	12	212	34	4	"	"	22	48	0	70
C66	825°	750°	1	725°	$\frac{1}{4}$	212	33	3	"	760°	28	48	0	76
C67	"	"	"	"	1	212	34	4	"	"	20	0	3	23
C68	"	"	"	"	4	207	33	3	"	"	14	48	7	69
C69	"	"	"	"	12	202	33	3	"	"	17	48	4	69
C70	"	"	"	"	16	179	32	2	"	"	3	0	8	11
C79	825°	750°	1	718°	$\frac{1}{4}$	207	34	4	"	760°	22	48	4	74
C80	"	"	"	"	1	192	34	1	"	"	15	0	6	21
C81	"	"	"	"	4	202	32	1	"	"	15	0	3	18
C82	"	"	"	"	12	196	32	1	"	"	0	0	3	3
C87	825°	750°	1	706°	$\frac{1}{4}$	196	32	3	"	760°	29	37	10	76
C88	"	"	"	"	1	192	33	3	"	"	25	42	14	81
C89	"	"	"	"	2	196	32	3	"	"	21	36	12	69
C92	825°	750°	1	740° to 718°	2	207	32	2	"	760°	18	48	4	70
C93	"	"	"	"	8	187	36	2	"	"	0	0	14	14
C96	"	"	"	740° to 706°	3	196	33	1	"	"	3	0	18	21
C97	"	"	"	"	12	187	32	4	"	760°	3	0	2	5
C99	825°	800°	1	"	...	217	36	4	"	"	18	48	5	71
C108	"	"	"	732°	1	228	38	3	"	"	31	48	6	85
C109	"	"	"	"	4	217	36	3	"	"	27	42	5	74
C110	"	"	"	"	12	217	36	4	"	"	33	46	5	84
C119	825°	800°	1	725°	$\frac{1}{4}$	228	38	3	"	760°	19	48	5	72
C120	"	"	"	"	1	223	35	4	"	"	16	48	7	71
C121	"	"	"	"	4	223	38	4	"	"	24	48	5	77
C122	"	"	"	"	12	212	32	3	"	"	19	0	7	26
C132	825°	800°	1	718°	$\frac{1}{4}$	217	38	3	"	760°	29	27	7	63
C133	"	"	"	"	1	196	33	2	"	"	6	48	3	57
C134	"	"	"	"	4	187	31	3	"	"	15	0	12	27
C135	"	"	"	"	12	187	31	2	"	"	0	0	6	6
C136	"	"	"	"	16	179	32	2	"	"	6	1	5	12

TABLE VIII.—(continued).

Reference Number.	Heat Treatment of Blanks.			Hardness of Blanks after Heat Treatment.	Hardening of Cutters. Quenching in Water.		Defectiveness of Cutters with Reference to Hardening Cracks.							
	First Furnace.		Second Furnace.		Temp. ° C.	Time. Hour.	Temp. ° C.	Time. Mins.	Thick End.	Middle.	Thin End.	Total.		
	Temp. ° C.	Time. Hour.												
C141	825°	1	800°	706°	1	202	32	4	760°	15	22	2	13	37
C142	"	"	"	"	"	196	31	3	"	"	32	46	8	86
C143	"	"	"	"	"	196	32	3	"	"	12	45	5	62
C148	825°	1	800°	740° to 718°	1	228	38	4	760°	15	13	48	0	61
C149	"	"	"	"	"	217	35	4	"	"	10	48	1	59
C150	"	"	"	"	"	223	36	4	"	"	39	48	3	90
C151	"	"	"	"	"	207	33	4	"	"	37	12	6	55
C154	"	"	"	740° to 706°	3	192	32	2	"	"	12	45	13	70
C155	"	"	"	"	12	187	30	3	"	"	0	0	1	1
C157	825°	1	850°	...	...	241	38	5	760°	15	11	48	0	59
C166	"	"	"	732°	1	228	38	5	"	"	14	48	3	65
C167	"	"	"	"	4	223	35	5	"	"	15	48	0	63
C168	"	"	"	"	12	217	34	4	"	"	17	48	6	71
C177	825°	1	850°	725°	1	228	36	6	760°	15	15	48	1	64
C178	"	"	"	"	"	228	39	5	"	"	19	48	5	72
C179	"	"	"	"	"	212	33	5	"	"	20	48	4	72
C180	"	"	"	"	12	187	31	4	"	"	10	0	1	11
C189	825°	1	850°	718°	1	241	38	5	760°	15	14	48	3	65
C190	"	"	"	"	1	202	33	4	"	"	24	48	7	79
C191	"	"	"	"	4	196	32	3	"	"	15	0	9	24

C192	"	"	"	"	"	12	187	32	3	"	"	9	24	5	38
C197	825°	850°	1	706°	1	$\frac{1}{2}$	212	34	5	760°	15	34	48	6	88
C198	"	"	"	"	"	1	217	32	3	"	"	31	27	15	73
C199	"	"	"	"	"	2	207	32	3	"	"	17	48	4	69
C202	825°	850°	1	740° to 718°	1	2	228	38	5	760°	15	20	48	4	72
C203	"	"	"	"	"	8	207	33	4	"	"	18	48	10	76
C206	"	"	"	740° to 706°	"	3	202	31	4	"	"	30	48	3	81
C207	"	"	"	"	"	12	183	29	4	"	"	6	32	12	50
C209	825°	900°	1	732°	1	...	255	39	6	760°	15	13	48	0	61
C218	"	"	"	"	"	4	241	38	6	"	"	12	48	2	62
C219	"	"	"	"	"	4	241	40	5	"	"	7	48	2	57
C220	"	"	"	"	"	12	241	38	6	"	"	13	48	7	68
C229	825°	900°	1	725°	1	$\frac{1}{2}$	262	43	6*	760°	15	10	48	4	62
C230	"	"	"	"	"	1	248	40	5	"	"	10	48	0	58
C231	"	"	"	"	"	4	228	35	5	"	"	26	48	0	74
C232	"	"	"	"	"	12	196	32	4	"	"	3	0	2	5
C242	825°	900°	1	718°	1	$\frac{1}{2}$	248	40	5	760°	15	15	48	1	64
C243	"	"	"	"	"	1	217	36	6	"	"	12	48	8	68
C244	"	"	"	"	"	4	207	34	3	"	"	32	36	10	78
C245	"	"	"	"	"	12	207	35	3	"	"	6	0	8	14
C246	"	"	"	"	"	16	201	34	2	"	"	3	0	2	5
C251	825°	900°	1	706°	1	$\frac{1}{2}$	241	37	5	"	"	7	48	3	58
C252	"	"	"	"	"	2	228	35	3	760°	15	24	48	0	72
C253	"	"	"	"	"	2	223	36	4	"	"	22	48	0	70
C256	825°	900°	1	740° to 718°	1	2	269	42	6	760°	15	7	48	0	55
C257	"	"	"	"	"	8	228	36	6	"	"	8	38	3	59
C260	"	"	"	740° to 706°	"	3	228	35	5	"	"	8	48	2	58
C261	"	"	"	"	"	12	192	33	4	"	"	3	48	6	57

* Ease of machining varied considerably in different parts of blank.

bars,¹ or again, it is interesting to observe the progress of the recalescence, as shown by bars which were water-quenched after heat treatment, and to trace the relationship between this progress and the liability of the corresponding cutters to crack on hardening. Such comparisons cannot be made without the necessity of close attention as to the exact process referred to in each particular case; but no great difficulty will arise, if Tables I. to V. (pp. 137-141) are studied and clearly apprehended.

Change in Length of Test Bars due to Normalising.

260 bars were normalised by heating to 825° C. for one hour and then cooling in air. The change in length due to this process was slight and has not been shown in the tables. Twenty-five bars showed no change in length. Forty-four bars lengthened by an average amount of 0.0002 inch, whilst 191 bars shortened by an average of 0.0005 inch. The change in 211 bars, out of the total of 260, was within the limits of + 0.0002 and - 0.0007 inch.

Modulus of Elasticity of Hardened Test Bars.

Dr. Hatfield reports that he had the figures for the modulus of elasticity carefully worked out for all of the 254 bars which underwent the bending test; and the value was found, in every case, to be between 12,000 and 12,500 tons per square inch. He states further that the slight variations within these limits are more likely to be due to irregularities in testing than to persistent variations due to the treatment of the bars. This constancy of the modulus is all the more remarkable in view of the fact that the series consisted of bars which had undergone, before hardening, the great variety of treatment shown in Tables I. to V. The standard hardening through which every one of the 254 bars passed, before undergoing the bending test, was, of course, conducted with very little variation from beginning to end.

¹ The expression, "the corresponding water-quenched bars," denotes the bars which were water-quenched from a heat treatment the same as was given to the sand-cooled blanks from which the cutters in question were made; and further, that such bars are being considered in their condition after such water-quenching and before the standard hardening.

Hardness of Hardened Test Bars.

The Brinell test was applied at a point $\frac{5}{8}$ inch from the end of each of the 254 bars which underwent the standard hardening, and 246 of them gave a reading of over 700. The eight bars which gave lower readings were retested nearer the end, and then they also showed over 700. The Shore test gave readings varying only from 90 to 95 for the whole series of 254 bars, with half a dozen slight exceptions.

Hardness of Test Bars and Cutter Blanks after Heat Treatment.

Many bars differed considerably in hardness from blanks which had been similarly heat-treated, as shown by both the Brinell and Shore tests, sometimes the bar and sometimes the blank being the harder. The ratio of the Brinell figure to the Shore figure was always, with two or three trifling exceptions, higher for bars than for the corresponding blanks after heat treatment. Taking the case of bars only, the Brinell-Shore ratio was very variable. The following are given as examples of extreme cases. Two bars¹ gave the same Brinell reading of 652, but the Shore figures were 97 and 67 respectively. Two other bars² gave the same Shore reading of 41, but the Brinell figures were 460 and 241 respectively. There is no particular reason to suppose that the variations were frequently caused by irregularities either in preparing the specimens or in testing them. They may represent inherent differences in the actual condition of the steel, according to the heat treatment.

Brinell-Shore Ratio in Relation to Hardening Cracks.

Cutters made from blanks, which gave a relatively high Brinell-Shore ratio were specially liable to hardening cracks. It is true that blanks which gave low ratios produced both good and bad cutters; but, on the other hand, there were 32 blanks, out of the total number of 102, which gave a ratio above 6.2; and all of these, with two exceptions,³ showed a hardening

¹ Bars B9a and B46.

² Bars B16a and B242.

³ Even in the two exceptional cases the defectiveness figures were as high as 18 and 37 respectively.

defectiveness of 50 or more. This subject is dealt with further in Appendix VI.

Miscellaneous Treatments.

Two test bars, B1 and B2, and two test cutters, C1 and C2, were subjected to the standard hardening, without previous normalising or heat treatment. The steel, having been annealed by the steelmaker, was soft, and the machining number was 2. One of the bars cracked in hardening, and both of them gave rather poor results under bending stress. Both cutters broke badly, as was confidently expected. They are shown in Fig. 9, Plate VIII., and the references are explained in Fig. 8.

Two test bars, B3 and B4, and two test cutters, C3 and C4, underwent standard hardening after the normalising, the heat treatment being omitted. The normalised pieces were decidedly hard, although the cutter blanks were quite capable of being machined without much trouble. Both of the bars cracked in hardening, and the bending test results were rather poor. Both cutters were badly broken, as shown in Fig. 9. Cutter C3 did not actually break in two; but the crack extended all the way round, and full marks were given for the defectiveness in the centre. Probably no importance attaches to the fact that the defectiveness figures for the two cutters are 65 and 86 respectively, and in this connection reference should be made to the latter part of the paragraph on "Defectiveness of Test Cutters" (see p. 164).

Inasmuch as the basis of most of the heat treatments was an hour's heating at a temperature of 750°, 800°, 850°, or 900° C., followed by soaking at a lower temperature, it was decided that the experimental work should include the usual triplicate series of two test bars and one cutter for each of these four temperatures, the soaking at the lower temperature being omitted. That is to say, the pieces were heated for an hour to one or other of the four temperatures shown above, and were then quenched in water, or cooled in sand, direct from the first furnace. Fig. 9 shows cutters C45, C99, C157, and C209, which in the blank were heat-treated in this way, and were then hardened by the standard process. The increase in the hardness of the

blanks with the higher temperatures of heat treatment will be noticed. All the cutters were badly broken. The bars corresponding to these cutters gave the results that were expected of them.

*Heat Treatments consisting of Single Heats at, or below,
the Change Ac1.2.3. (See Table I.)*

Forty test bars and 17 test blanks were heat-treated at single temperatures of 739°, 732°, 725°, or 718° C. Some of the results from the water-quenched bars, after heat treatment and before the standard hardening, are shown in Fig. 10. The bars heated to 718° and to 725° shortened considerably on quenching and remained soft; and, so far as hardness was concerned, there was no progressive change taking place with prolonged heating. At 732° a considerable degree of hardness was reached; but the results suggest that the complete change Ac1.2.3 would not be accomplished at this temperature, however much the time were prolonged. Some curious results were obtained at 732° which are discussed in Appendix VII. At 739° the complete change Ac1.2.3 took place gradually. An extra bar, B9a, treated at this temperature for two hours and quenched in water, gave the exceptionally high Shore figure of 97, although the Brinell reading was only 652. The temperature record for the two hours at 739° is shown in Fig. 29 (p. 213). A micrograph of this bar after the heat treatment (it never underwent the standard hardening) is shown in Fig. 11, Plate XV. It would have been interesting to test the magnetic properties of all the bars and blanks immediately on removal from the furnace, but this was not thought of at the time.

The test cutters, corresponding with the bars referred to above, are shown in Fig. 12, Plate IX. After the blanks had undergone the heat treatments shown, the cutters made from them were all hardened by the standard process, and there is a fair sequence in the results, although the heat treatments were given at various times, over a period of thirteen months, which allowed ample opportunity for discrepancies to arise in the temperature control. None of the blanks which were sand-cooled from 739° C. were very soft, and all the cutters made from them broke badly in

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
None.	Various Temperatures.	Water.	
Hardness and Change in Length.			

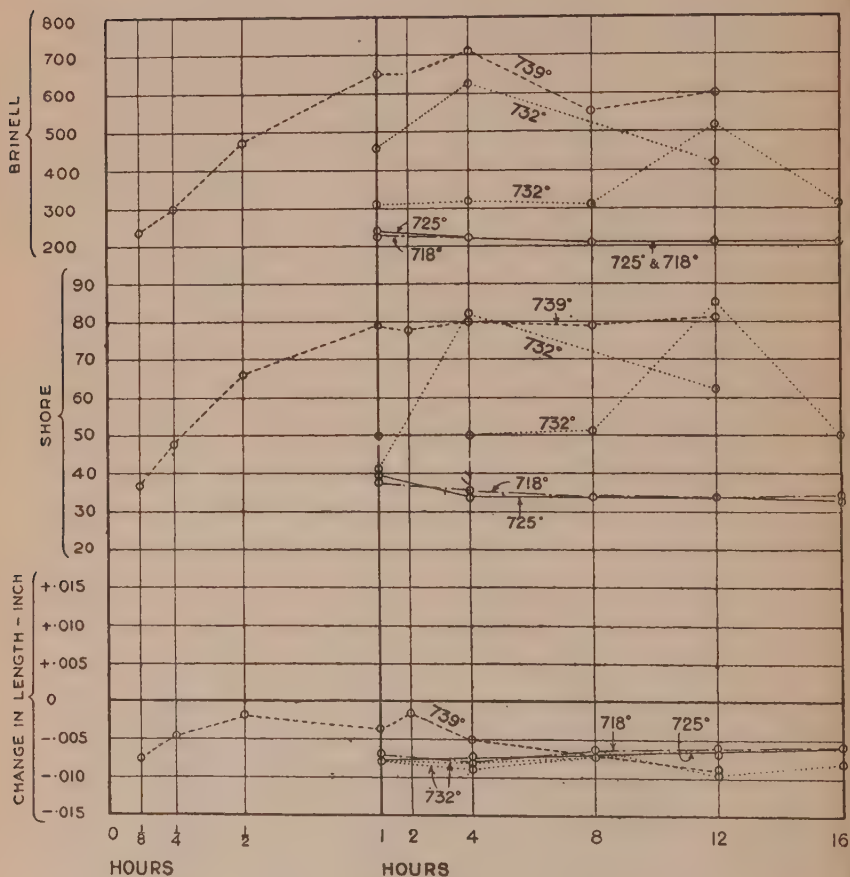


FIG. 10.

hardening. The blanks treated at 732°, 725°, and 718° C. for one hour, and for four hours, were unsatisfactory; but most of the blanks treated at these temperatures for eight, twelve, and sixteen hours were very soft, and two of them had the exceptional machining-number of 1; moreover, the cutters made from them were mostly good. It is noticeable that C25 was worse than C24, which may be due to chance; or it may be the case that at 732°, prolonged for sixteen hours, a desirable change had been fully accomplished and a further change had begun. Perhaps the best result would be obtained by prolonging the heat at 718° even longer than sixteen hours. The hardness alone is of no value as a guide to the condition of a steel with regard to its liability to crack in hardening; for example, blanks C22, C22a, and C33 all give Brinell 207, Shore 35, and machining-number 2; but the defectiveness of the cutters made from the first two was 51 and 45 respectively, whilst the defectiveness of the cutter made from the third was only 6, and this contrast is quite in accord with experience.

Turning again to the test bars in this group, it may be noted that, after the standard hardening, the ones which showed the least change in length were those which had been heat-treated at 725° or 718° C., and on the other hand some of the bars which had been at 739° C. shortened very considerably. There were bars from each of the heat treatments of 739°, 732°, 725°, and 718° C., both water-quenched and sand-cooled, which after the standard hardening gave very high figures in the bending tests; for example, bar 739°-4 hours water-quenched, showed a maximum stress of 196 tons per square inch and 95 foot-lbs. of energy; and bar 725°-4 hours sand-cooled, had an elastic limit of 147 tons per square inch, and took 89 foot-lbs. of energy.

Heat Treatments consisting of 750° C. in First Furnace, and Various Temperatures in Second Furnace. (See Table II.)

Fig. 13 refers to test bars which had been water-quenched after heat treatment and before the standard hardening. The temperature in the first furnace was 750° C. for one hour in all cases. The second furnace varied in temperature as shown. The recalescence was almost complete in fifteen minutes at

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
750°c	Various Temperatures.	Water.	
Hardness and Change in Length.			

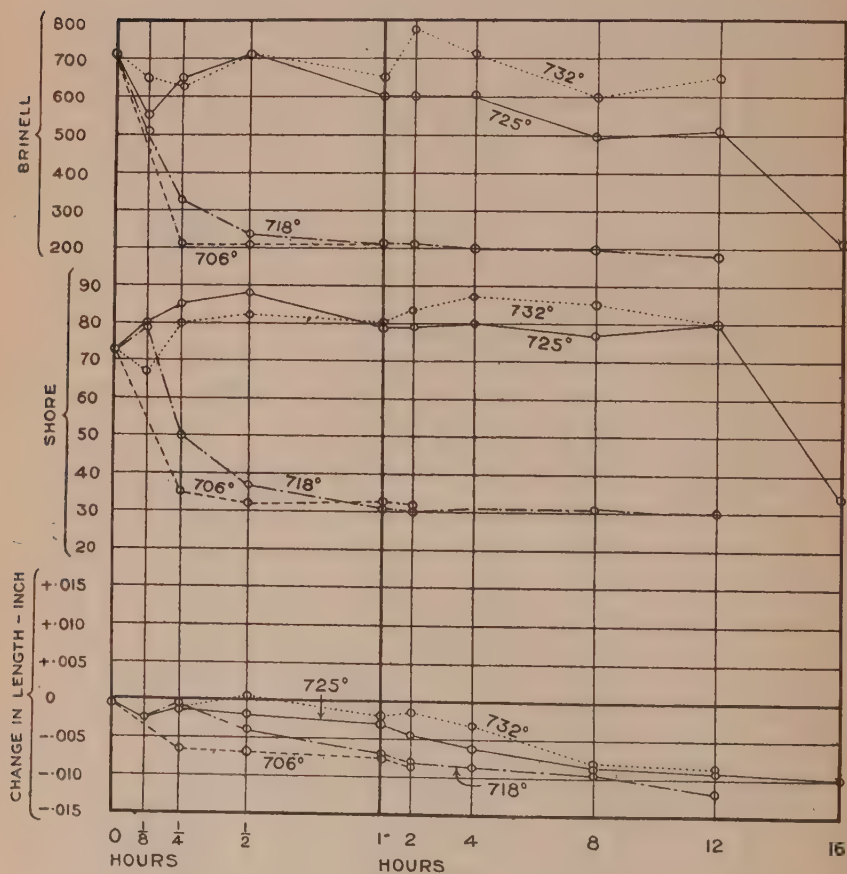


FIG. 13.

706° C., and it took something over half an hour at 718°. The three bars quenched after one, four, and twelve hours respectively at 718° C. were almost as soft as the corresponding bars, not shown in the diagram, which were cooled in sand. At 725° and 732° the recalescence apparently made very little progress in twelve hours; but the form of the Brinell and Shore curves may be consistent with the accomplishment of part of the Ar3.2.1 change. The fall after sixteen hours at 725° is probably due to a difference of 2° or 3° in working. Nearly a year elapsed between the heat treatment of the twelve-hour and sixteen-hour bars, and a discrepancy was afterwards found to exist in the standardisation of the pyrometer. The figures for the change in length are plotted out at the bottom of Fig. 13 and are fairly consistent.

The results shown in Fig. 13 may be compared with those shown on Table IX. (p. 178). It must be remembered that the comparison is made between bars which were heat-treated and water-quenched but not yet subjected to standard hardening, on the one hand; and, on the other hand, hardened cutters made from blanks which had been similarly heat-treated, but sand-cooled. Table IX. shows the defectiveness figures for the thick end, middle, and thin end of the cutters, and also the total defectiveness in each case. The 732° cutters¹ all broke badly on hardening. The lower temperatures with prolonged heats produced good results; and the only unaccountable figure in the table is the low defectiveness-number, of only 23, for the 725°-1 hour cutter. The results obtained from the falling heats² are quite in keeping with the behaviour of the cutters which had been subjected to the fixed temperatures shown. Tables IX. to XII. are dealt with further in Appendix VIII.

Reverting to the test bars in this 750° group. Of those which were sand-cooled from the heat treatment the ones soaked at 706° and 718° were decidedly the softest, as would be expected, and after the standard hardening these bars showed much the smallest change in length. Some bars from all of the second furnace temperatures gave very high figures in the bending

¹ The expression "732° cutters" is an abbreviation for the cutters of this 750° group which, in the blank, were soaked at 732° in the second furnace.

² This expression is used for cases in which the temperature fell uniformly, in the second furnace, from 740° to 718° or to 706°.

TABLE IX.

Heat Treatment.				Hardening.				
First Furnace. 1 Hour.		Second Furnace. Various Times.		Cooling.				
750°		Various Temperatures		Sand				
Defectiveness of Test Cutters.								
Time (Hours) in Second Furnace.								
		1.	2.	3.	4.	8.	12.	16.
750°	S. 17+48+3 =68	...	...	...	...	...	...	...
750°	...	C. 24+48+0 =72	...	...	S. 37+48+3 =88	...	S. 22+48+0 =70	...
750°	S. 28+48+0 =76	S. 20+0+3 =23	...	...	S. 14+48+7 =69	...	S. 17+48+4 =69	S. 3+0+8 =11
750°	S. 22+48+4 =74	S. 15+0+6 =21	...	...	S. 15+0+3 =18	...	S. 0+0+3 =3	...
750°	...	S. 29+37+10+25+42+14+21+36+12 =81	S. 29+37+10+25+42+14+21+36+12 =69	...	...	...	...	...
750°	...	...	S. 18+48+4 =70	...	...	S. 0+0+14 =14	...	...
750°	...	...	...	S. 3+0+18 =21	...	...	S. 3+0+2=5	...

The letters "S" and "C" show whether the corresponding sand-cooled bars were sound or cracked after the standard hardening.

TABLE X.

Heat Treatment.			Hardening.
First Furnace, 1 Hour.	Second Furnace, Various Times.	Cooling.	
800° C.	Various Temperatures	Sand	
Defectiveness of Test Cutters.			

First Furnace, ° C.	Cooled direct from First Furnace.	Temperature of Second Furnace.	Time (Hours) in Second Furnace.									
			$\frac{1}{4}$.	$\frac{1}{2}$.	1.	2.	3.	4.	8.	12.	16.	
800°	C. 18+48+5 =71	...	...	...	...	...	...	...	...	...	...
800°	...	732°	...	...	S. 31+48+6 =85	...	...	S. 27+42+5 =74	...	S. 33+46+5 =84	...
800°	...	725°	C. 19+48+5 =72	...	C. 16+48+7 =71	...	...	S. 24+48+5 =77	...	S. 19+0+7 =26	...
800°	...	718°	C. 29+27+7 =63	...	C. 6+48+3 =57	...	...	S. 15+0+12 =27	...	S. 0+0+6 =6	S. 6+1+5 =12
800°	...	706°	...	C. 22+2+13 =37	S. 32+46+8 =86	C. 12+45+5 =62	...	...	...	...	...
800°	...	740°-718°	...	...	C. 13+48+0 =61	C. 10+48+1 =59	...	S. 39+48+3 =90	S. 37+12+6 =55	...	...
800°	...	740°-706°	...	...	...	...	C. 12+45+13 =70	...	...	S. 0+0+1 =1	...

The letters "S" and "C" show whether the corresponding sand-cooled bars were sound or cracked after the standard hardening.

TABLE XI.

Heat Treatment.				Hardening.					
First Furnace. 1 Hour.		Second Furnace. Various Times.		Cooling.					
850° C.		Various Temperatures		Sand					
Defectiveness of Test Cutters.									
Time (Hours) in Second Furnace.									
First Furnace. ° C.	Cooled direct from First Furnace.	Temperature of Second Furnace.	1.	2.	3.	4.	8.	12.	16.
850°	C. 11+48+0 =59	...	...	...	...	...	...	...	...
850°	...	732°	...	...	...	S. 15+48+0 =63	...	S. 17+48+6 =71	...
850°	...	725°	S. 15+48+1 =64	...	...	C. 20+48+4 =72	...	S. 10+0+1 =11	...
850°	...	718°	C. 14+48+3 =65	...	...	S. 15+0+9 =24	...	S. 9+24+5 =38	...
850°	...	706°	S. 34+48+6 =88	S. 24+48+7 =79	...	...	...	...	...
850°	...	740°-718°	...	S. 31+27+15 =73	C. 20+48+4 =72	...	S. 18+48+10 =76	...	...
850°	...	740°-706°	...	...	C. 30+48+3 =81	...	...	S. 6+32+12 =50	...

The letters "S" and "C" show whether the corresponding sand-cooled bars were sound or cracked after the standard hardening.

TABLE XII.

Heat Treatment.			Hardening.
First Furnace. 1 Hour.	Second Furnace. Various Times.	Cooling.	
900° C.	Various Temperatures	Sand	

Defectiveness of Test Cutters.

First Furnace °C.	Cooled direct from First Furnace.	Temperature of Second Furnace.	Time (Hours) in Second Furnace.							
			1.	2.	3.	4.	8.	12.	16.	
900°	S. 13+48+0 =61	...	...	...	...	...	...	...	...
900°	...	732°	C. 12+48+2 =62	...	...	C. 7+48+2 =57	...	C. 13+48+7 =68	...	
900°	...	725°	C. 10+48+0 =58	...	...	S. 26+48+0 =74	...	S. 3+0+2 =5	...	
900°	...	718°	C. 12+48+8 =68	...	...	S. 32+36+10 =78	...	S. 6+0+8 =14	S. 3+0+2 =5	
900°	...	706°	S. 7+48+3 =58	S. 22+48+0 =70	...	...	...	...	...
900°	...	740°-718°	...	C. 7+48+0 =55	...	...	S. 18+38+3 =59	...	...
900°	...	740°-706°	...	...	C. 8+48+2 =58	...	...	S. 3+48+6 =57	...	

The letters "S" and "C" show whether the corresponding sand-cooled bars were sound or cracked after the standard hardening.

tests, those soaked at 732° being as good as the others. The 732° -2 hour bar, which was water-quenched from the heat treatment and finally hardened, broke with a maximum stress of 188 tons per square inch, total deflection 4.17 millimetres and 94 foot-lbs. of energy.

Heat Treatments consisting of 800° C. in First Furnace, and Various Temperatures in Second Furnace. (See Table III.)

Fig. 14 refers to test bars which had been water-quenched after heat treatment and before they underwent standard hardening, and Table X. (p. 179) shows the corresponding cutters. Prolonged soaking of the blanks at 718° produced fairly good cutters, and twelve hours at 725° was a step in the right direction.

Fig. 15 shows the change in length of the corresponding bars which had been sand-cooled and then hardened, and which, therefore, underwent the same processes throughout as the cutters. The bars which had been soaked at 718° show the least change in length. Bar 706° -2 hours is odd, and it gave remarkable results in the bending test also. Taken as a whole, the results of the bending tests on these hardened 800° bars are much inferior to those obtained from the hardened 750° bars.

Heat Treatments consisting of 850° C. in First Furnace, and Various Temperatures in Second Furnace. (See Table IV.)

Fig. 16 refers to test bars which had been water-quenched after heat treatment and before they underwent the standard hardening. It will be noticed that many of the bars show a slight increase in length, due to the high temperature of 850° in the first furnace. In many cases the bending test results from this group were better than those from the 800° group, though of course inferior to the results from the 750° group. Table XI. (p. 180) shows the defectiveness of the corresponding cutters, which are nearly all badly broken. Cutter 718° -12 hours had a defectiveness of 38, which is the only irregular result. It might reasonably have been expected to be about 8 or 10.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
800°C	Various Temperatures.	Water.	
Hardness and Change in Length.			

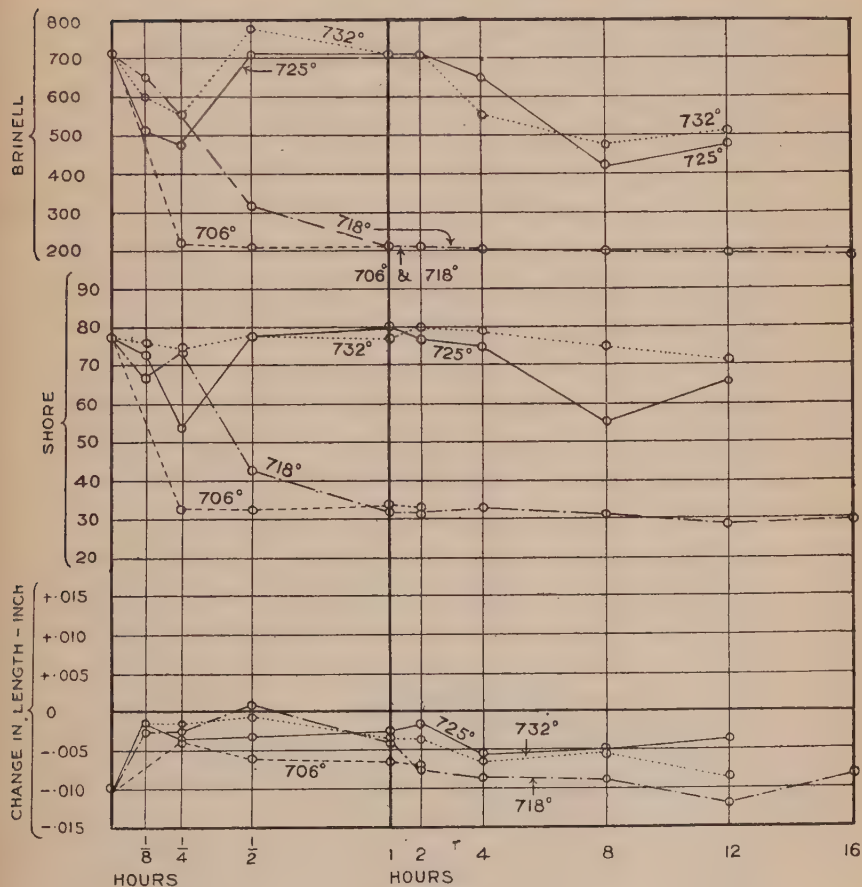


FIG. 14.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	760°c for 20 Minutes
800°c	Various Temperatures	Sand	
Hardness and Change in Length.			

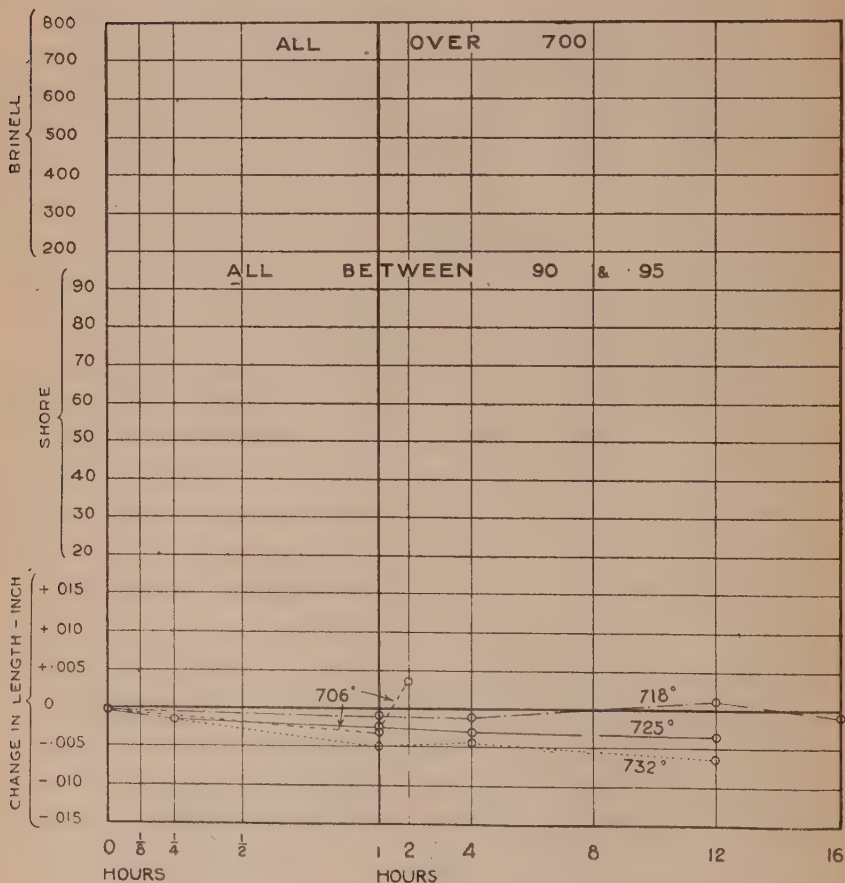


FIG. 15.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	
850°C	Various Temperatures.	Water.	
Hardness and Change in Length.			

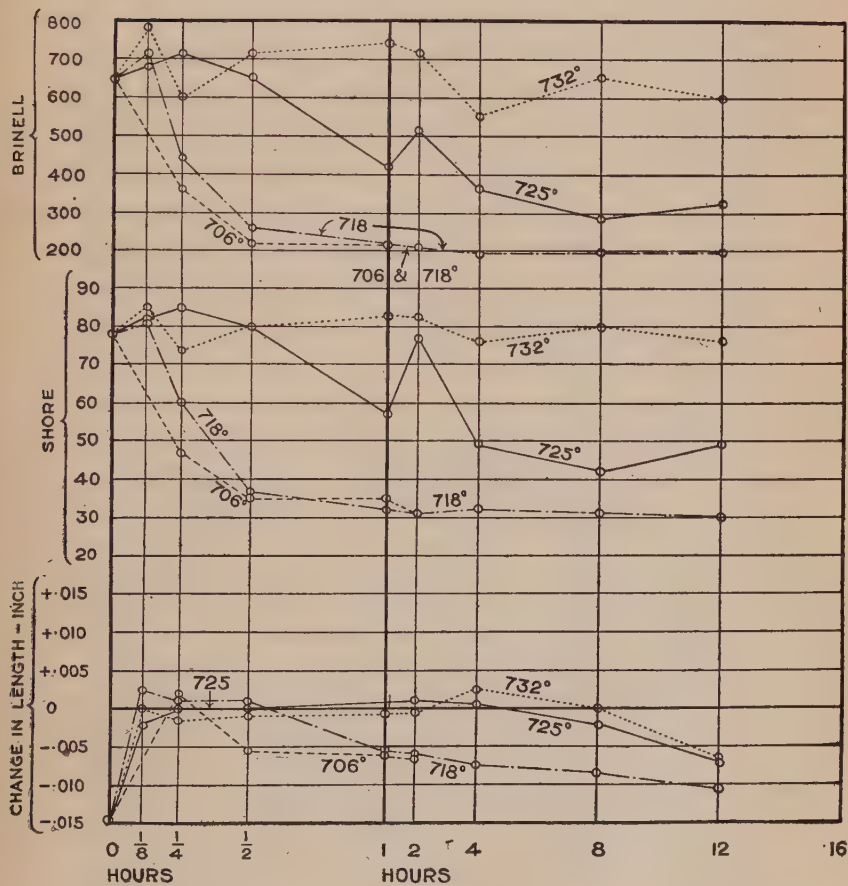


FIG. 16.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
900°C	Various Temperatures.	Water.	
Hardness and Change in Length.			

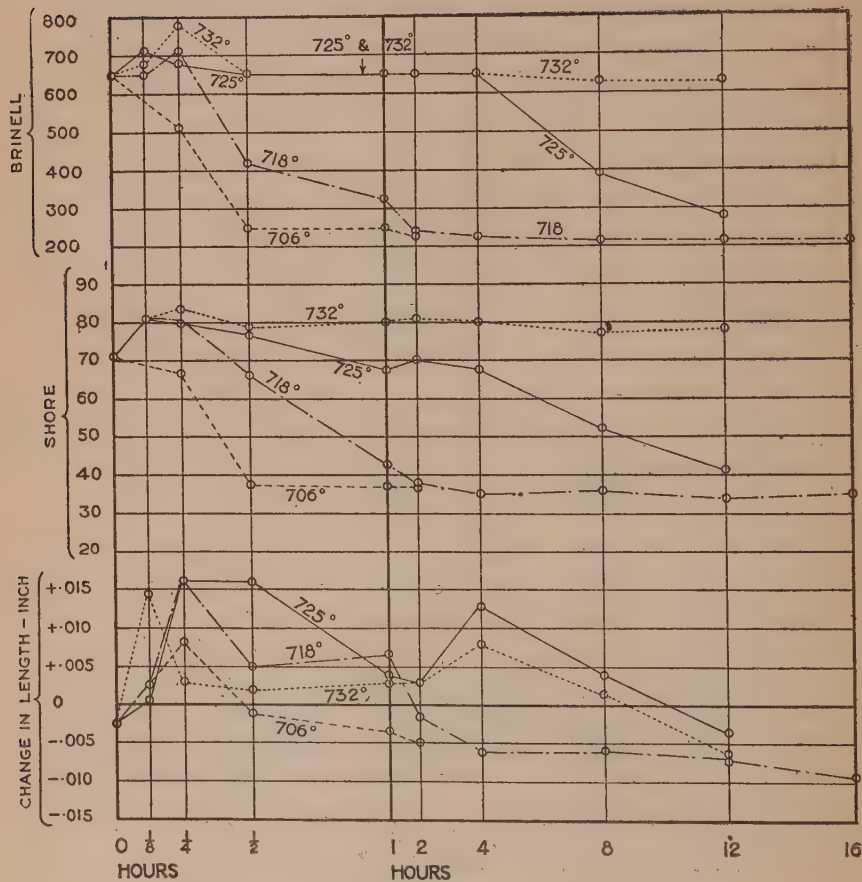


FIG. 17.

Heat Treatments consisting of 900° C. in First Furnace, and Various Temperatures in Second Furnace. (See Table V.)

Fig. 17 refers to test bars which had been water-quenched after the heat treatment and before they underwent the standard hardening. Many of the bars lengthened considerably, as may be expected when the temperature of about 880° C. is exceeded. Further investigation is needed as to whether the remarkable irregularities in the curves showing the change in length are due to definite changes in the steel, corresponding to the treatment shown. Fig. 18 shows the change in length of the same bars, due to the subsequent standard hardening. The figures are consistent but the number of observations was reduced by hardening breakages. The corresponding sand-cooled bars (not shown in the figure) show but little change in length on hardening, which accords with experience. The 900° bars gave poor results under the bending test. Table XII. (p. 181) shows the defectiveness of the corresponding cutters. The results are all fairly in accordance with expectation, the only good cutters being those which, in the blank, were soaked for long periods at 725° or 718° C.

Heat Treatments consisting of Various Temperatures in the First Furnace, and 732° C. in the Second Furnace.

In Fig. 19 some results which have been dealt with in previous pages are rearranged in a new grouping. The bars which were heated to only 750° in the first furnace retained their capacity for hardening quite as well as those which had been at higher temperatures. The diagram of change in length shows the customary elongation, slight at 850° and pronounced at 900°. Fig. 20, Plate X., shows the cutters made from the corresponding blanks, and all are, of course, badly broken.

Heat Treatments consisting of Various Temperatures in the First Furnace, and 725° C. in the Second Furnace.

From Fig. 21 it would appear that the recalescence took place at 725° more readily in the bars that had been heated to 850° and 900° than in those which were heated to only 750° and 800°; but these irregular results, as explained in Appendix VIII.,

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	
900°C	Various Temperatures.	Water.	760°C for 20 Minutes
Hardness and Change in Length.			

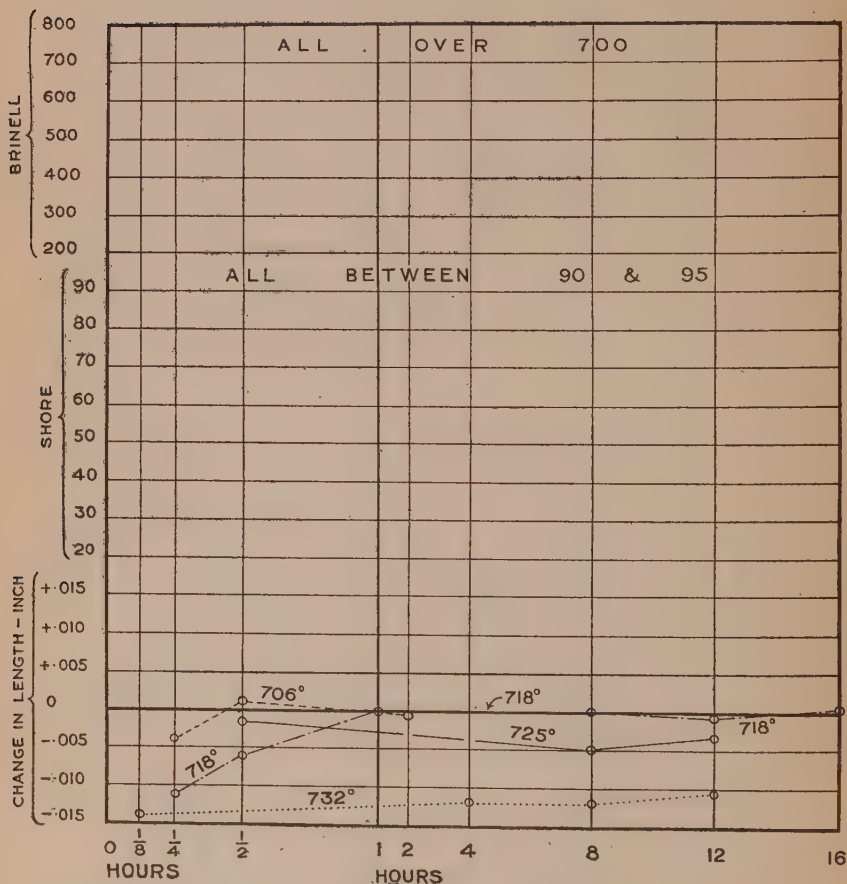


FIG. 18.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
Various Temperatures.	732°C	Water.	
Hardness and Change in Length.			

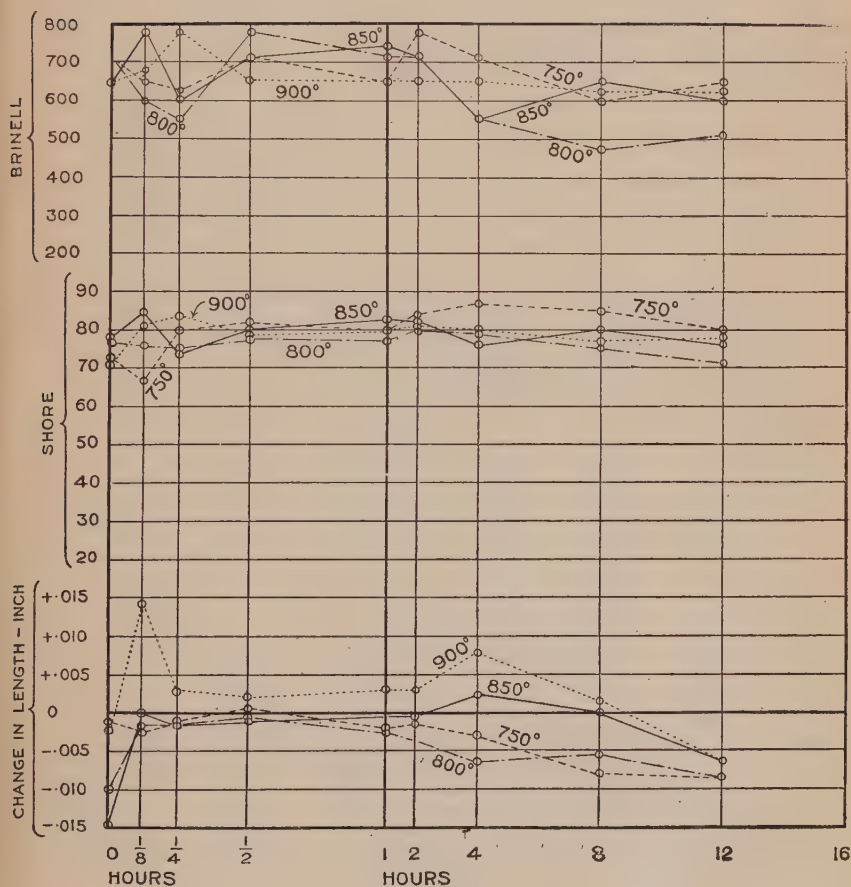


FIG. 19.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
Various Temperatures.	725°C	Water.	
Hardness and Change in Length.			

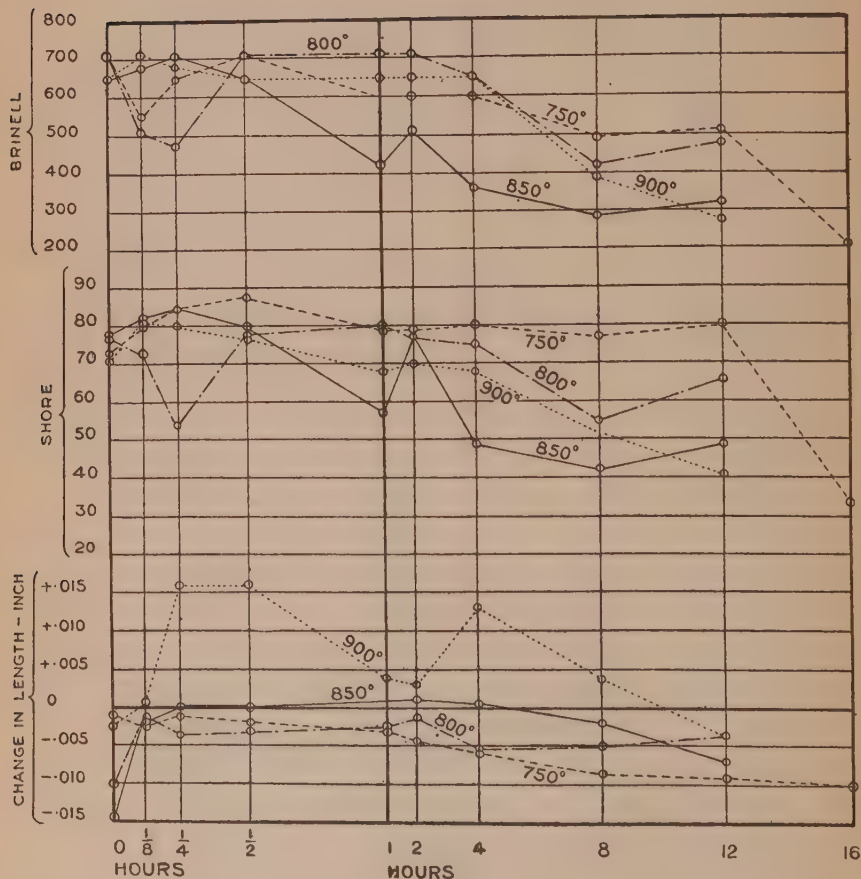


FIG. 21.

are probably due to an error of about 3° in the regulation of the second furnace temperature. The change in length shown in Fig. 21 is consistent, and should be compared with the corresponding changes shown in Figs. 19, 23, and 26. The corresponding cutters are shown in Fig. 22, Plate XI. Cutter C69, which broke badly in hardening (see Appendix IX.), was soft in the blank after heat treatment, and was machined more easily than the blanks for cutters C180 and C232, which hardened with but slight defectiveness. Cutter C232 shows the smallest defectiveness in this group; but, judging by the bending test in the corresponding bars, the steel is in a poor condition compared with the steel in C69 or C70.

Heat Treatments consisting of Various Temperatures in the First Furnace, and 718° C. in the Second Furnace.

In Fig. 23 it is seen that a temperature of 718° in the second furnace allows most of the recalescence to take place in an hour or two, and thereafter the sand-cooled bars (not shown in the figure) were very little softer than those quenched in water from the heat treatment. Fig. 24 shows bending test results obtained from the corresponding bars which were sand-cooled instead of water-quenched, and which finally underwent the standard hardening. The inferiority of the bars that were heated to 900° is clearly shown. Some high figures were obtained from bars that had been heated to 750° , 800° , or 850° C. Fig. 25, Plate XII., shows the corresponding cutters, amongst which there are a number of fairly good ones. The most noteworthy are those made from blanks that were heated to 750° and soaked at 718° ; which show low figures under Brinell and Shore tests, and were exceptional in giving the lowest machining-number. It is easy to harden cutters by processes which leave them sound but in a poor condition, and treatments which produce the best cutting edge are commonly amongst the most risky with regard to hardening cracks. It is, therefore, specially interesting to note that some of the cutters which are fairly sound, shown in Fig. 25, correspond with bars which gave very high figures in the bending tests, and they would undoubtedly stand up remarkably well in work.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. 1. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	None.
Various Temperatures.	718°C	Water.	
Hardness and Change in Length.			

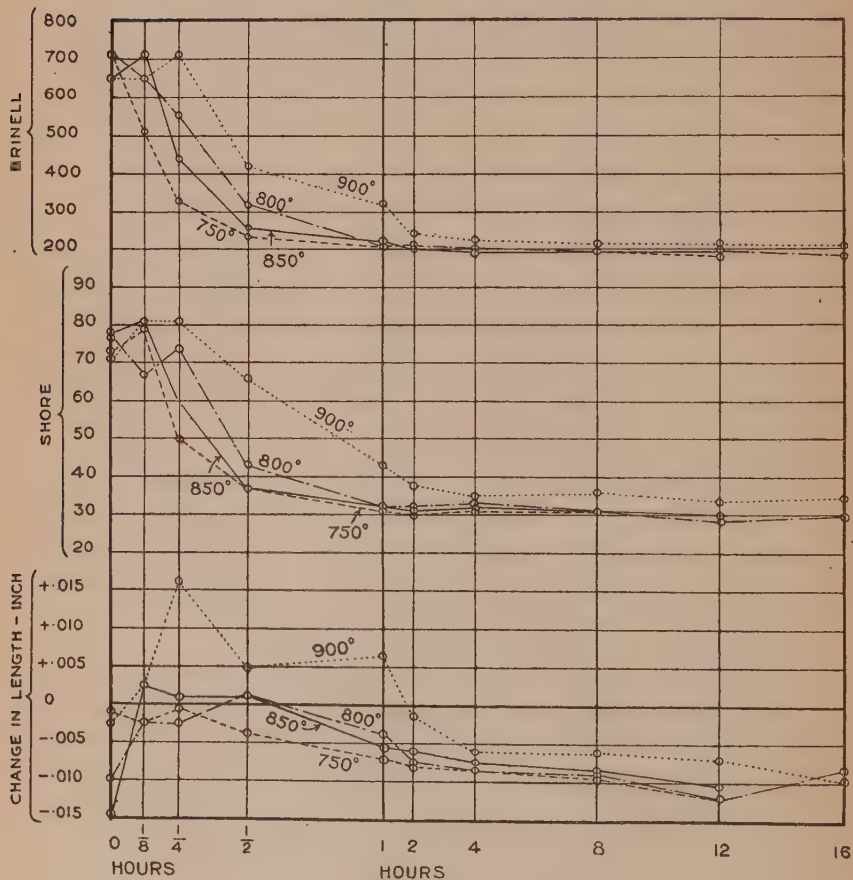


FIG. 23.

HEAT TREATMENT			HARDENING.
FIRST FURNACE. I. HOUR.	SECOND FURNACE. VARIOUS TIMES.	COOLING	
Various Temperatures.	718°C	Sand	760°C for 20 Minutes
Bending Tests.			

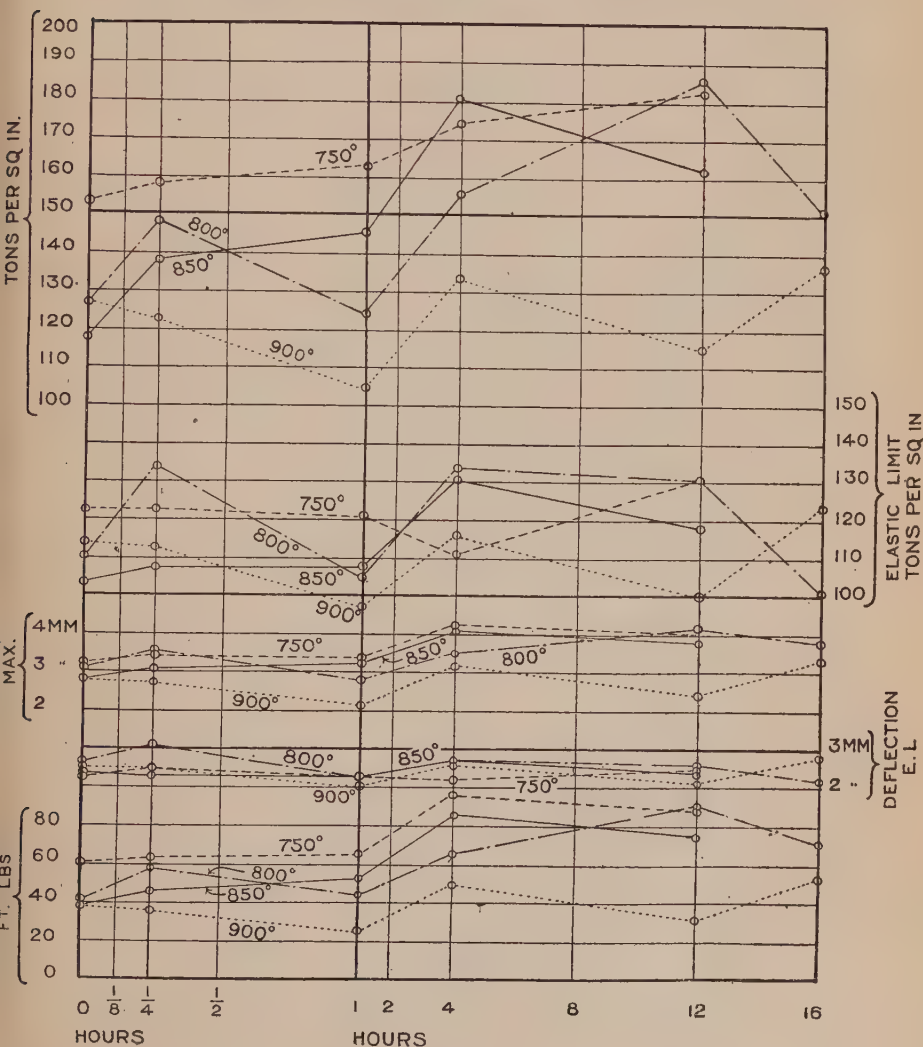


FIG. 24.

HEAT TREATMENT			HARDENING.
FIRST FURNACE 1. HOUR	SECOND FURNACE. VARIOUS TIMES.	COOLING	None
Various Temperatures	706°C	Water.	
Hardness and Change in Length.			

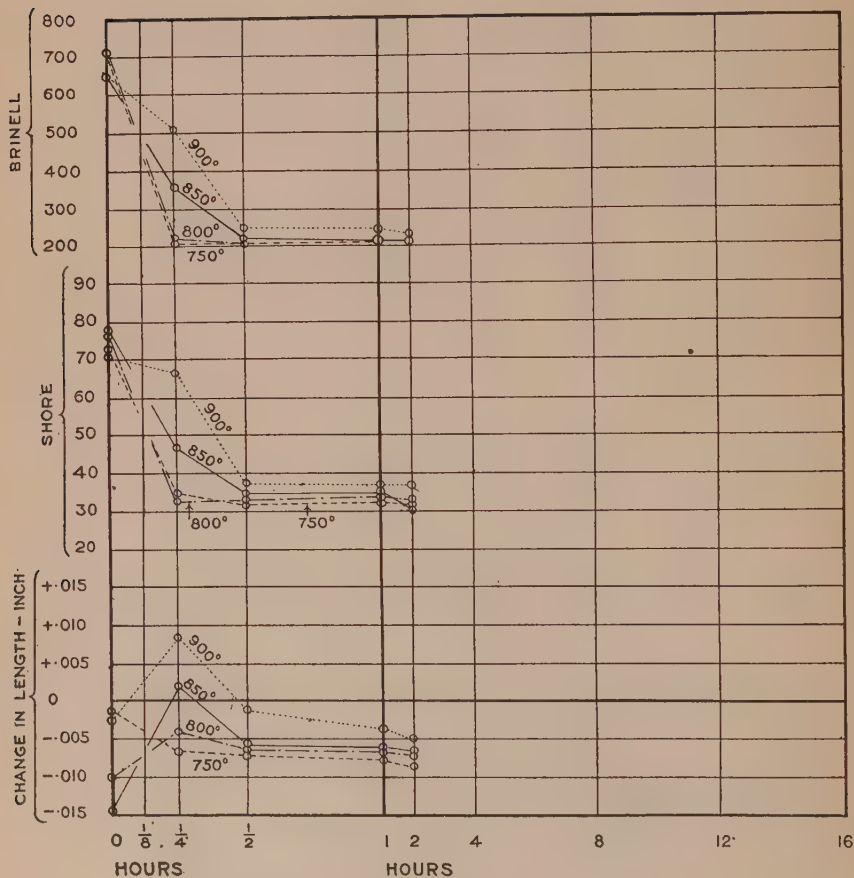


FIG. 26.

Heat Treatments consisting of Various Temperatures in the First Furnace, and 706° C. in the Second Furnace.

In Fig. 26 it is shown that at 706° the recalescence is almost complete in half an hour. Fig. 27, Plate X., shows the corresponding cutters which are all badly broken, although C141 has scarcely cracked in the centre. It was not thought necessary in this group to prolong the soaking beyond two hours, as it was supposed that no further change was likely to occur at this low temperature.

Heat Treatments consisting of Various Temperatures in the First Furnace, and Falling Heats in the Second Furnace.

In Fig. 28, Plate XIII., particulars are given of eighteen cutters which, in the blank, were cooled uniformly in the second furnace, from 740° to 718° or to 706°, in various periods of time, as shown. Some good results were obtained, and the figures generally are consistent except that the high machining-number of 4 for cutter C97 appears improbable.

PART IV.

CONCLUSION.

In the following paragraphs some comments are made upon the experimental work, in the light of the experience obtained in carrying it out. Some of the results are summarised, and suggestions arising therefrom are tentatively offered.

The Cracking of Test Bars.

Many of the bars cracked around the hole with water-quenching, and in these cases the intention to ascertain the change in length was frustrated. Some value attached, however, to the cracks, as showing the relation between the treatment given and the liability of the steel to crack in subsequent hardening. For the sake of the length measurement it would have been better to use bars without holes, although this course would have involved the slight disadvantage of handling them by tongs instead of by wires.

The Use of Magnetic Tests.

In all the heat treatments in the neighbourhood of the change Ac1.2.3, both in heating up to that temperature and in cooling to a point below it, useful knowledge might have been obtained by applying a magnetic test to the bars and blanks when they were ready for removal from the furnace.

The Use of the Salt-Bath.

Considering the time taken fully to reach a given temperature, even when immersed in a liquid and with frequent stirring (see Appendix II.), it is evident that the time necessary for precision treatment would be unduly prolonged if the heating were accomplished in any other way. It was felt that the salt-bath method of heating was clearly the right one. The use of a liquid in frequent motion ensured that the pieces were evenly heated throughout, and that the pyrometer showed the temperature of the work. In view of the accuracy demanded for research

work of this character, it would have been an improvement if a continuous stirring of the pyromelt had been provided for.

Progressive Changes in Length after Hardening.

The change in length of the test bars should have been ascertained at a fixed length of time soon after each process, and again at various periods, and after boiling in water. In the absence of such methods, slight errors no doubt arose. These precautions were, however, taken in connection with thirteen of the bars, and the results suggest that if all the bars had been similarly dealt with, some valuable data would have been obtained by way of correlating progressive changes in length with the heat treatment prior to hardening. (See Appendix III.)

Relation between the Change in Length and the Heat Treatment.

Of the test bars which were quenched from the heat treatment (measured after such quenching and before the standard hardening), some which had been heated up to 850° lengthened slightly, and many which had been heated up to 900° lengthened greatly, the amount in extreme cases being over 0.015 inch. The bars which were heat-treated with a maximum temperature of 750° or 800° C. shortened with water-quenching.

Many bars which were sand-cooled from certain heat treatments were afterwards found to show a change in length due to the standard hardening of only about 0.001 inch or less, and specific treatments can be given to ensure a minimum change in length on hardening.

Modulus of Elasticity Constant Throughout.

254 test bars were all hardened by one standard treatment after undergoing very diverse heat treatment (involving maximum temperatures varying from 718° to 900° C., for different periods of time from $7\frac{1}{2}$ minutes up to 17 hours), followed by water-quenching in some cases and sand-cooling in others. After these hardened bars had been under the bending test the modulus of elasticity was calculated in every case, and was found to be constant throughout at about 12,250 tons per square inch. (See p. 170.)

Relation between Bending Test Results and Heat Treatment.

With the exception of the modulus of elasticity the 254 hardened test bars referred to above were found under the bending test to differ greatly amongst themselves, as would be expected. Very high figures were obtained from the bars which were not subjected to a higher temperature than 750° in the heat treatment and, in some instances, from bars which had been heated to 800° and to 850° . The bars heated to 900° gave relatively poor results. (See pp. 175-191.)

Hardness Constant Throughout after Standard Hardening.

There was very little difference in the hardness of the 254 bars referred to above after they had undergone the standard hardening, the Brinell figure throughout being over 700 and the Shore about 92. (See p. 171.)

High Brinell-Shore Ratio of Cutters which Cracked Badly on Hardening.

The test cutters which cracked badly on hardening were generally made from blanks which gave a relatively higher ratio of the Brinell figure to the Shore figure. Of the test bars which were water-quenched from the heat treatment, those corresponding to cutters of high defectiveness gave a conspicuously higher ratio than those corresponding to good cutters. (See p. 171 and Appendix VI.)

Ac1.2.3 at 738° C. Test Bars and Blanks Heated to 739° .

In accordance with the evidence of heating curves the change Ac1.2.3 was considered to be complete at 738° . Bars heated for an hour or more to 739° evidently passed through the change, those which were water-quenched being very hard. Cutters made from blanks which had been heated to this temperature all broke badly on hardening. (See pp. 173-175.)

TABLE XIII.

Ref. Number.	Heat Treatment.			Hardening.	Change in Length due to Hardening.										Nett Change in Length due to Hardening.
	First Furnace.	Second Furnace.	Cooling.		Change in Length due to Heat Treatment.	Temp.	(In each case the difference given is not the total, but only the change since the previous measurement.)								
							1 Hour. °C.	Hours.	Inch.	Time. °C.	Thousandths of Inches.				
											14 Days.*				
											2 Hours.	1 Day.	2 Days.	4 Days.		A.	B.
B28	...	725°	8	Water	760°	20	-2.1	-0.3	0	0	-0.3	-0.4	-0.0031		
B29	...	"	12	"	"	"	+1.2	-0.2	-0.1	-0.1	-0.2	-0.4	+0.0002		
B30	...	"	16	"	"	"	+0.6	-0.1	-0.2	0	-0.4	-0.3	-0.0004		
B35	...	"	"	Sand	"	"	-0.4	-0.1	0	0	-0.3	-0.3	-0.0011		
B38	...	718°	12	Water	"	"	+0.7	-0.1	-0.1	-0.1	-0.3	-0.5	-0.0004		
B39	...	"	16	"	"	"	+0.6	-0.2	0	-0.1	-0.4	-0.4	-0.0005		
B43	...	"	"	Sand	"	"	+1.0	-0.1	0	0	-0.3	-0.4	+0.0002		
B65	750°	725°	16	Water	760°	20	-1.0	-0.3	-0.1	0	-0.4	-0.2	-0.0020		
B70	"	"	"	Sand	"	"	+1.8	-0.2	-0.2	0	-0.3	-0.5	+0.0006		
B131	800°	718°	16	Water	760°	20	-1.0	-0.1	0	-0.1	-0.3	-0.2	-0.0017		
B136	"	"	"	Sand	"	"	-0.5	0	0	0	-0.3	-0.4	-0.0012		
B241	900°	718°	16	Water	760°	20	+1.2	-0.1	-0.1	0	-0.2	-0.5	+0.0003		
B246	"	"	"	Sand	"	"	-1.5	0	-0.1	0	-0.3	-0.3	-0.0022		

Before the heat treatment shown above, all the bars were normalised by heating to 825° C. for 1 hour and cooling in the air.

* Fourteen days after hardening the bars were measured and the results are shown in column A. The bars were then boiled in water for ten minutes and measured three hours later. The results are shown in column B.

Test Bars and Blanks Heated to 732° C.

Bars showed an interesting change on heating to 732°, and were decidedly hard with water-quenching. Bars cooled to ¹732° from higher temperatures indicated that some change towards recalescence was in progress, but they were generally harder than bars simply heated to this temperature. Some of the cutters made from blanks which were simply heated up to 732° hardened satisfactorily, but all the cutters made from blanks cooled to this temperature broke badly. (See pp. 173-191 and Appendix VII.)

Test Bars and Blanks Heated to 725° C.

Bars heated to 725° and quenched in water were quite soft, but bars cooled to 725° from higher temperatures and then quenched were decidedly hard; in both cases, however, a change was in progress, and some of the cutters made from the blanks soaked, both in heating and cooling, at 725° hardened satisfactorily. (See pp. 173-191.)

Heating or Cooling to 732° or 725° C.

There was nothing in the results inconsistent with the supposition that if the soaking were considerably prolonged, say to thirty or forty hours, the steel would reach the same condition by heating up to 732°, or cooling to 732° from a higher temperature. The same statement applies with respect to a temperature of 725°.

Test Bars and Blanks Heated to 718° C.

Bars heated up to 718° for four hours and longer were very similar to bars cooled for similar periods of time to 718° from higher temperatures. They were quite soft on quenching in water, but an important change had taken place, as shown by the fact that most of the cutters made from blanks so treated hardened satisfactorily. (See pp. 173-191.)

¹ The expression "cooled to" implies that the pieces were heated to a higher temperature in the first furnace, and after being transferred to the second furnace they were cooled to, and soaked at, the temperature of that furnace.

Blanks Cooled to 706° C.

All the cutters made from blanks cooled to 706° from higher temperatures broke badly on hardening, but the longest time of soaking was only two hours. It was assumed that the desired condition could not be attained at such a comparatively low temperature, but this assumption was not tested with a prolonged heat at 706°. (See pp. 175-191.)

Ac1.2.3 in Stages. A Range from 715° to 725° C.

The behaviour of the test bars and test cutters suggests that the changes Ac1.2.3 and Ar3.2.1 may take place in steps, and that definite stages corresponding with certain temperatures may be reached provided that sufficient time is allowed for the process. Apparently there is a range of temperature of somewhere about 715° to 725° within which, with prolonged soaking, the steel reaches a condition in which the liability to hardening cracks is reduced to a minimum. The range may be the same for heating and for cooling if the process be sufficiently prolonged; but for practical purposes, and with limited time, the range may be taken as a trifle higher for heating than for cooling.

Some Cutter Blanks might be Water-Quenched from Heat Treatment.

There were many blanks which would have been quite soft enough to be machined easily if they had been water-quenched from the heat treatment, and had such water-quenched blanks been made in addition to the blanks which were sand-cooled useful information would probably have resulted, by way of locating more precisely the range within which the desirable change is brought about.

Suggestion for Investigating Ac1.2.3 and Ar3.2.1.

The changes Ac1.2.3 and Ar3.2.1 might well be investigated by the method of heating (and also of cooling) small bars at various temperatures and for various times, followed by quenching

in water. Small bars could be provided in such large quantities that sufficient of them could be used in each series to allow of quenching at short intervals over a long period of time, up to twenty or thirty hours. The process should be carried out for each temperature with two series of bars treated simultaneously in the same furnace. One series would simply be heating to the given temperature; whilst the other series, having been previously raised to a higher temperature, would be cooling at the given temperature.

Suggestion for Standard Hardening Test.

It appears that good steel is commonly subject to much difference of condition, after annealing, with regard to the liability of articles made from it to crack in hardening. (See p. 135.) The liability to change in shape also varies greatly. It is therefore desirable that there should be a recognised standard of hardening behaviour, which might be specified and verified as easily as the analysis or the tensile properties. Hardening tests might be carried out cheaply and quickly. For example, it would be simple to saw test discs of a given thickness from bars of steel. Such discs might be jig-drilled, according to an agreed standard which would render them very liable to hardening cracks, and then subjected to a specified heating and quenching. The guidance given by such a test would save much loss in hardening, and steel which failed in the test would, if it were otherwise suitable, only require to be re-annealed.

Applicability of this Research to Industry.

The work described in this paper may appear to demand special furnaces and delicate apparatus, such as can only be associated with a laboratory. It may be supposed that there is a great gap between such work and its application to industry; and yet the author is prepared to say that it is practicable to control the processes within the required limits, under workshop conditions, and with the ordinary labour available. The method of heating in a liquid, both for annealing and for hardening, can readily be carried out with a degree of precision which is surprising to those

who have not been accustomed to it, and the control of the temperature is all the easier when a large mass is being dealt with.

This research has been confined to one particular steel, which was chosen because it is largely used for certain classes of work ; but there is no reason to doubt that various steels covering a wide range would respond in a similar way. If careful work were given on these lines to the investigation of other steels, much useful knowledge would be obtained. An annealing treatment which practically eliminated the risk of distortion or breakage would give the hardener confidence to heat and quench his work, regardless of any consideration but the production of the best possible cutting edge or wearing surface ; and this would lead to a great increase of efficiency, because in present day practice the treatment required to produce the maximum cutting or wearing condition is necessarily modified to save the articles from cracking or warping.

The results published in this paper represent only a small fraction of the matter available ; and they must be taken as the product of much more than the isolated research under review, being in fact the outcome of experiments and observations extending over many years. It is agreed that, even in the case of the most difficult articles, there is no mysterious fate to decree inexplicable breakages or failures ; and this paper is offered as a contribution to an understanding of the well-known difficulties connected with tool steel hardening. It is hoped that the information given may be useful both to the maker and user of steel, and that the expression "as true as steel" may be justified again and again, even more than it has been in the past.

Acknowledgments.

The author has pleasure in recording his thanks to his wife, who has done a great amount of work in arranging and tabulating the results ; and to his brother, Mr. E. Russell Brayshaw, who has shared in the whole of the work, and without whose help and co-operation it could not have been carried through. Thanks are given to Dr. W. H. Hatfield for undertaking the mechanical testing, the actual work of which was ably carried out by the

staff of the Brown-Firth Research Laboratories, to whom the author is much indebted. Finally, thanks are given to Mr. H. James Yates who, as chairman of Brayshaw Furnaces and Tools, Ltd., gave permission for the results to be published.

APPENDIX I.

HEATING AND COOLING CURVES.

Heating and cooling curves are mentioned on p. 144, and reference is made to Figs. 4 and 5. The platinum resistance coil was enclosed in a thin porcelain tube and connected with a Callendar Recorder. Obviously the arrangement was not sensitive enough to record quick changes of temperature, but it was suitable for the purpose intended, namely, to show the thermal changes in a piece of steel of the size indicated when heated and cooled slowly. In the curve which was taken in the shortest time (not reproduced), the period between the halt in heating and the halt in cooling was about 55 minutes, whilst the longest time between the changes (see Fig. 4) was about $2\frac{1}{2}$ hours. In cases like these a moderate amount of lag in the pyrometer is not important. Inasmuch as any heating or cooling of the steel necessarily implies a variation of temperature throughout the mass, it follows that there must also be a variation in the advancement of the Ac or Ar change, and the curves obtained show the nett result in the centre of the specimen, so far as temperature is concerned. Such a nett result is of more importance for the purpose of this investigation than indications obtained from a very small specimen of steel, in which the complication of heat gradients is negligible. The halt in heating occurred about 738°C . The halt Ar3.2.1 took place at 716°C . when cooling from a maximum temperature of 760°C ., and at 712° when cooling from 930° . Both at 716° and at 712° the halt was followed by a rise in temperature of about 4°C . The increase in the rate of heating at a high temperature (see Fig. 4) was due merely to the regulation of the gas burners. The desired maximum temperature was not being reached in the appointed time, so the rate of heating was accelerated by increasing the gas supply.

APPENDIX II.

TIME REQUIRED FOR HEATING IN THE SALT-BATH.

The method of heating is described on pp. 147-148, and the following additional information is given. At 900° C. the bars were noticeably cooler than the tray after two and a half minutes' immersion, but they appeared to be fully up to the temperature in five minutes. The blanks apparently took about fifteen minutes to reach the full temperature when immersed at 900° C., and twenty minutes when immersed at 750° C. Blanks C54, C55, and C56, which were by mistake heated to 740° instead of 750° C., appeared to take about thirty minutes to reach the temperature of the furnace, and their behaviour drew attention to an error in the recorder, which would, however, have been discovered in any case. The slow heating of these bars was, of course, natural in view of the proximity of the change Ac1.2.3. Blanks which had been heated to 900° C. for an hour were distinctly hotter than the second furnace after five minutes at 732° C., but no difference was noticeable after seven and a half minutes. The pieces were of course always allowed their scheduled time in the furnace, without regard to the times given above as being required for reaching the temperature of the furnace.

APPENDIX III.

CHANGE IN LENGTH OF TEST BARS.

The change in length of the test bars is referred to on p. 151, and the following additional information is given. After the heat treatment the bars were boiled in water for a few minutes, and the measurement of length was made at a period of time varying from two to four months afterwards. About eight months later the bars were measured again, and it was found that many had lengthened or shortened slightly, but in most cases the difference was less than half a thousandth of an inch. The figures shown in the tables are the ones first obtained and the changes subsequently discovered have been ignored. No doubt if measurements had been taken a few hours after the heat treat-

ment, and before boiling, the figures so obtained would have differed from those given. After the bars had undergone the standard hardening they were all, with the exception of the thirteen referred to below, boiled in water for a few minutes, and then measured for length within a few days. In consequence of a suggestion from Dr. Hatfield, thirteen bars were measured at definite periods of time after the hardening, without first boiling in water, and progressive changes were observed, as shown in Table XIII. (p. 199). Furthermore, the bars after being measured on the fourteenth day were boiled for ten minutes, and then after standing for three hours they were measured again. It will be seen that the effluxion of time and the boiling caused the bars to shorten considerably. The table as a whole shows how indeterminate was the length, particularly when it is noticed that the heat treatments given to the bars in question would presumably have left them in a stable condition, whereas many of the other bars received heat treatments which must have left them in a state of severe strain. Table XIII. suggests that if all the bars had been measured soon after hardening, without boiling, and again at intervals over a period of months, and also after boiling, the value of the information obtained would have been greatly enhanced.

APPENDIX IV.

BENDING TESTS.

The following is Dr. Hatfield's description of the carrying out of the bending tests. A 50-ton tensile testing machine was used. The sound bars were on rigid supports at $5\frac{1}{4}$ inches span, but for the cracked bars the supports were only 5 inches apart. In all cases of 5-inch supports corrections have been made, and the figures are given as for $5\frac{1}{4}$ inches throughout. The tool applying the load to the bar, at the centre of the span, was attached to the lower shackle of the machine, and the load, corresponding to deflections increasing by small increments, was read off from the machine. The deflections were measured by a reading microscope supported on the platform of the machine and focussed on a point on the upper tool applying the load. The data observed were the deflections up to elastic limit, maximum

deflection before fracture of the bar, the load at elastic limit, and the maximum load. The elastic limit values were determined by plotting a graph in each case, indicating the relationship between load and deflection. From the data observed the "apparent stress" at elastic limit, and the "apparent maximum stress" on the bar, were calculated from the usual formula for flexure of beams:

$$f = \frac{3Wl}{2bd^2}$$

when

f = the fibre stress at the upper or lower surface of the bar.

l = the span.

b and d = the breadth and depth of the section of the beam.

W = the corresponding load.

From the area of the graphs determinations were made of the work involved in bending each beam up to fracture. The value of the modulus of elasticity was calculated according to the formula:

$$E = \frac{W}{\delta} \cdot \frac{l^3}{4bd^3}$$

when E = modulus of elasticity.

$\frac{W}{\delta}$ = ratio of load to deflection within the truly elastic region.

APPENDIX V.

THE MACHINING OF THE CUTTER BLANKS.

The cutter blanks were ground and tested for hardness after the heat treatment, and were then machined up into test cutters. The boring and turning were carried through by an experienced turner, who assigned to each blank a "machining-number" according to the ease or difficulty of working. These numbers were given without any knowledge of the Brinell or Shore figures, and will be found, in some cases, not to run parallel with them. The machining-numbers may be taken as indicating the grade of the steel from the point of view of a piece-worker engaged upon it. There were six grades or groups as follows:

1. (6 blanks.) Softer than normal. These blanks were machined with conspicuous ease, leaving a good smooth surface.
2. (17 blanks.) Normal. This group included blanks C1 and C2, which were machined up as received from the steelmaker, and without normalising or heat treatment.

3. (28 blanks.) Slightly harder than No. 2. The steel in this group would probably be used commercially without complaint.
4. (27 blanks.) Slightly harder than No. 3. The steel in this group also would be used commercially, but complaint would probably be made.
5. (15 blanks.) Slightly harder than No. 4. The blanks in this group could be machined without serious difficulty; but such steel would commonly be described as badly annealed, and would probably be returned to the steel-maker for re-annealing free of charge. This group included blanks C3 and C4, which were normalised but not heat-treated.
6. (9 blanks.) Slightly harder than No. 5. By running at a slower speed this steel could be machined without serious difficulty, but it was harder than would be accepted commercially for annealed steel.

After the blanks had been bored and turned the teeth were machined with a milling cutter $2\frac{3}{4}$ inches diameter, running at 67 revolutions per minute, the cutting speed being 48 feet per minute. The whole depth of tooth was taken at one cut with a table travel of $4\frac{1}{2}$ inches per minute. The cutting was easy in all cases, even for the blanks of machining-number 6. The milling cutter was sharpened after milling 12 test cutters from blanks of machining-numbers 1 and 2; but for the blanks of Nos. 3 to 6 it was sharpened after cutting every eight. The time which elapsed between the machining and the hardening was not noted, but it was about a week or two. There was no treatment for releasing any stresses set up by the machining.

APPENDIX VI.

RELATION BETWEEN HIGH BRINELL-SHORE RATIO AND TENDENCY TO CRACK IN HARDENING.

On pp. 171-172 it is shown that the cutters made from blanks which gave a high ratio of the Brinell figure to the Shore figure were specially likely to crack in hardening. A similar examination was made with respect to the sand-cooled bars corresponding

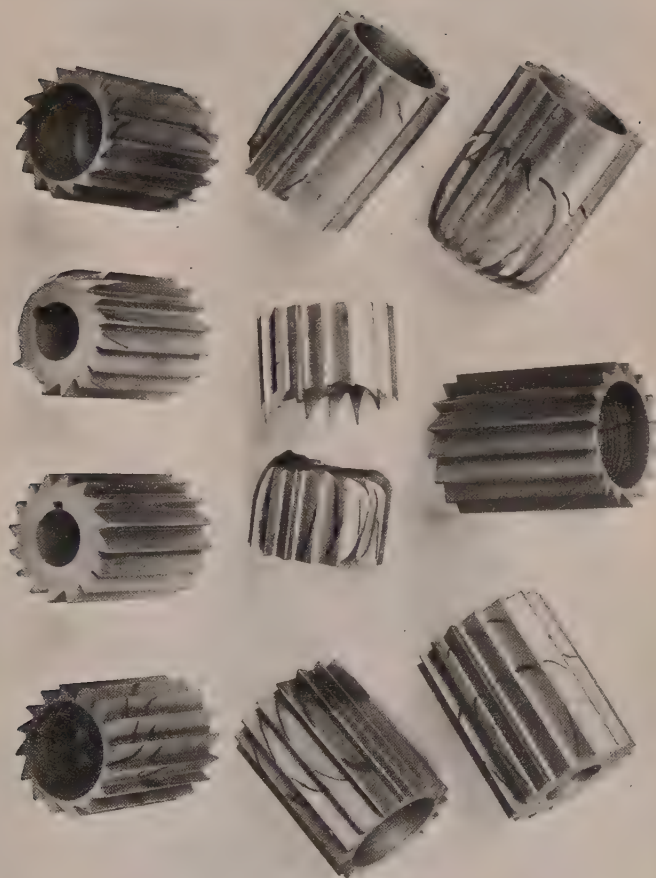


FIG. 2. Typical Group of Test Cutters after hardening.

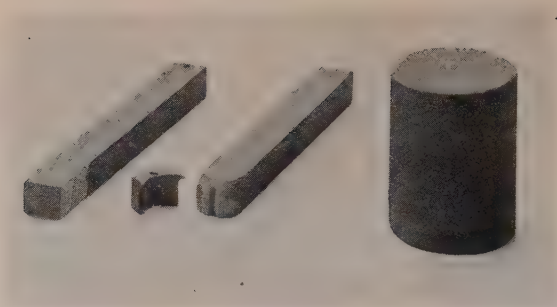


FIG. 3.
Cutter blank and Test Bars.

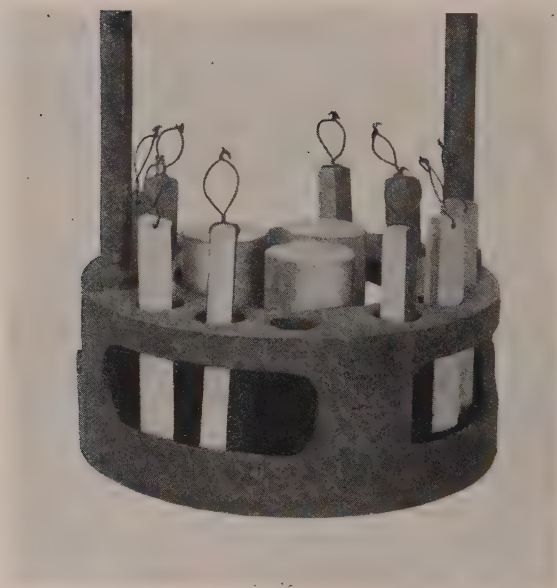


FIG. 7.
Special Tray for Salt Bath Furnace.

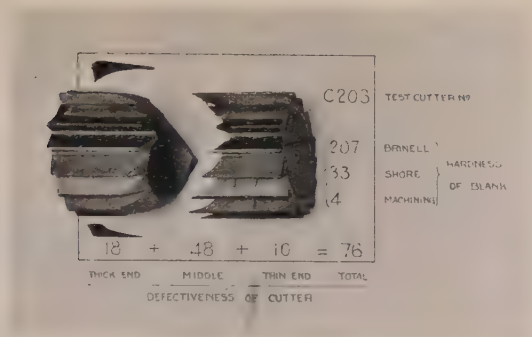


FIG. 8.

Typical Test Cutter, with explanation of figures.

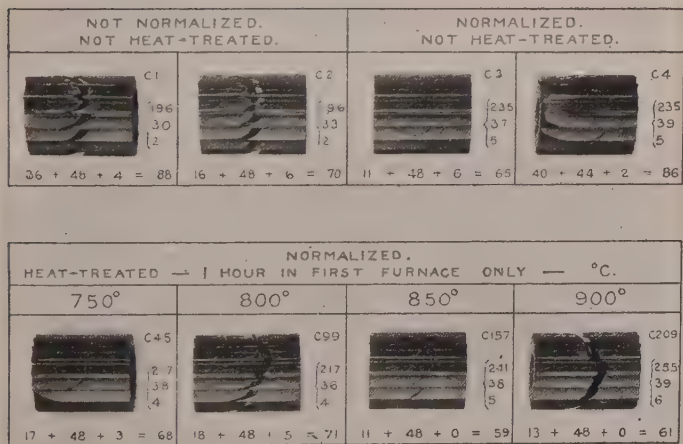


FIG. 9.

Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.

(For explanation of figures see Fig. 8, above.)

SINGLE HEATS.					
°C.	1 HOUR	4 HOURS	8 HOURS	12 HOURS	16 HOURS
739°	C13 10 + 48 + 2 = 60	C14 0 + 48 + 9 = 57		C15 17 + 38 + 10 = 65	
	C21 _a 21 + 48 + 5 = 74	C22 _a 9 + 27 + 9 = 45		C24 _a 0 + 0 + 4 = 4	
732°		C22 6 + 42 + 3 = 51	C23 3 + 0 + 5 = 8	C24 6 + 0 + 6 = 12	C25 15 + 3 + 8 = 26
	C31 27 + 48 + 6 = 81	C32 16 + 48 + 7 = 71	C33 3 + 0 + 3 = 6	C34 1 + 0 + 5 = 6	C35 6 + 0 + 7 = 13
718°				C42 8 + 0 + 7 = 15	C43 3 + 0 + 1 = 4

FIG. 12. Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.
(For explanation of figures see Fig. 8, Plate VIII.)





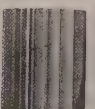







1 HOUR °C.	TIME AT 732°C.		
	1 HOUR	4 HOURS	12 HOURS
750°	 C54 212 37 4	 C55 207 33 4	 C56 212 34 4
	24 + 48 + 0 = 72	37 + 48 + 3 = 88	22 + 48 + 0 = 70
800°	 C108 228 38 3	 C109 217 36 3	 C110 217 36 4
	31 + 48 + 6 = 85	27 + 42 + 5 = 74	33 + 46 + 5 = 84
850°	 C166 228 38 5	 C167 223 35 5	 C168 217 34 4
	14 + 48 + 3 = 65	15 + 48 + 0 = 63	17 + 48 + 6 = 71
900°	 C218 241 38 6	 C219 241 40 5	 C220 241 38 6
	12 + 48 + 2 = 62	7 + 48 + 2 = 57	13 + 48 + 7 = 68

FIG. 20. Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.
(For explanation of figures see Fig. 8, Plate VIII.)





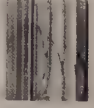







1 HOUR °C.	TIME AT 706°C.		
	1/2 HOUR	1 HOUR	2 HOURS
750°	 C87 196 32 3	 C88 192 33 3	 C89 196 32 3
	29 + 37 + 10 = 76	25 + 47 + 14 = 81	21 + 36 + 12 = 69
800°	 C141 202 32 4	 C142 196 31 3	 C143 196 32 3
	22 + 2 + 13 = 37	32 + 46 + 8 = 86	12 + 45 + 5 = 62
850°	 C197 212 34 5	 C198 217 32 3	 C199 207 32 3
	34 + 48 + 6 = 88	31 + 27 + 15 = 73	17 + 48 + 4 = 69
900°	 C251 241 37 5	 C252 228 35 3	 C253 223 36 4
	7 + 48 + 3 = 58	24 + 48 + 0 = 72	22 + 48 + 0 = 70

FIG. 27. Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.
(For explanation of figures see Fig. 8, Plate VIII.)

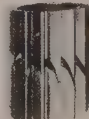
















1 HOUR °C.	TIME AT 725°C.				
	1/4 HOUR	1 HOUR	4 HOURS	12 HOURS	16 HOURS
750°	 C66 28 + 48 + 0 = 76 1212 33 3 100x	 C67 20 + 0 + 3 = 23 212 34 4 100x	 C68 14 + 48 + 7 = 69 207 33 3 100x	 C69 17 + 48 + 4 = 69 202 33 3 100x	 C70 3 + 0 + 8 = 11 179 32 2 100x
800°	 C119 19 + 48 + 5 = 72 228 38 3 100x	 C120 16 + 48 + 7 = 71 223 35 4 100x	 C121 24 + 48 + 5 = 77 223 38 4 100x	 C122 19 + 0 + 7 = 26 212 32 3 100x	
850°	 C177 15 + 48 + 1 = 64 228 36 6 100x	 C178 19 + 48 + 5 = 73 228 39 5 100x	 C179 20 + 48 + 4 = 72 212 33 5 100x	 C180 10 + 0 + 1 = 11 187 31 4 100x	
900°	 C229 10 + 48 + 4 = 62 262 43 6 100x	 C230 10 + 48 + 0 = 58 248 40 6 100x	 C231 26 + 48 + 0 = 74 228 35 5 100x	 C232 3 + 0 + 2 = 5 196 32 4 100x	

Fig. 22.

Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.
(For explanation of figures see Fig. 8, Plate VIII.)



















1 HOUR °C	TIME AT 718° C.				
	1/4 HOUR	1 HOUR	4 HOURS	12 HOURS	16 HOURS
750°	 C79 $\begin{matrix} 202 \\ 34 \\ 4 \end{matrix}$ $22 + 48 + 4 = 74$	 C80 $\begin{matrix} 192 \\ 34 \\ 1 \end{matrix}$ $15 + 0 + 6 = 21$	 C81 $\begin{matrix} 202 \\ 32 \\ 1 \end{matrix}$ $15 + 0 + 3 = 18$	 C82 $\begin{matrix} 196 \\ 32 \\ 1 \end{matrix}$ $0 + 0 + 3 = 3$	
800°	 C132 $\begin{matrix} 217 \\ 38 \\ 3 \end{matrix}$ $29 + 27 + 7 = 63$	 C133 $\begin{matrix} 196 \\ 33 \\ 2 \end{matrix}$ $6 + 48 + 3 = 57$	 C134 $\begin{matrix} 187 \\ 31 \\ 3 \end{matrix}$ $15 + 0 + 12 = 27$	 C135 $\begin{matrix} 187 \\ 31 \\ 7 \end{matrix}$ $0 + 0 + 6 = 6$	 C136 $\begin{matrix} 179 \\ 32 \\ 2 \end{matrix}$ $6 + 1 + 5 = 12$
850°	 C189 $\begin{matrix} 241 \\ 38 \\ 5 \end{matrix}$ $14 + 48 + 3 = 65$	 C190 $\begin{matrix} 202 \\ 33 \\ 4 \end{matrix}$ $24 + 48 + 7 = 79$	 C191 $\begin{matrix} 196 \\ 32 \\ 3 \end{matrix}$ $15 + 0 + 9 = 24$	 C192 $\begin{matrix} 187 \\ 32 \\ 3 \end{matrix}$ $9 + 74 + 5 = 88$	
900°	 C243 $\begin{matrix} 248 \\ 40 \\ 5 \end{matrix}$ $15 + 48 + 1 = 64$	 C244 $\begin{matrix} 217 \\ 36 \\ 6 \end{matrix}$ $12 + 48 + 8 = 68$	 C245 $\begin{matrix} 207 \\ 35 \\ 3 \end{matrix}$ $32 + 36 + 0 = 78$	 C246 $\begin{matrix} 201 \\ 34 \\ 2 \end{matrix}$ $6 + 0 + 8 = 14$	 C247 $\begin{matrix} 201 \\ 34 \\ 2 \end{matrix}$ $3 + 0 + 2 = 5$

FIG. 25.

Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.

(For explanation of figures see Fig. 8, Plate VIII.)




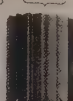



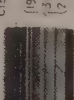

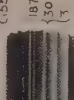








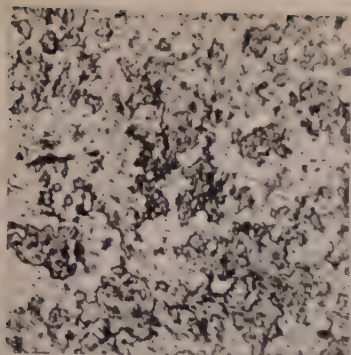
1 Hour °C.	COOLING FROM 740°C.					
	TO 718°C.		TO 706°C.		TO 706°C.	
	1 HOUR	4 HOURS	2 HOURS	3 HOURS	8 HOURS	12 HOURS
750°			 C92 $\begin{Bmatrix} 207 \\ 32 \\ 2 \end{Bmatrix}$ $18 + 48 + 4 = 70$	 C96 $\begin{Bmatrix} 196 \\ 33 \\ 1 \end{Bmatrix}$ $3 + 0 + 18 = 21$	 C93 $\begin{Bmatrix} 187 \\ 36 \\ 2 \end{Bmatrix}$ $0 + 0 + 14 = 14$	 C97 $\begin{Bmatrix} 187 \\ 32 \\ 4 \end{Bmatrix}$ $3 + 0 + 2 = 5$
800°	 C148 $\begin{Bmatrix} 228 \\ 38 \\ 4 \end{Bmatrix}$ $3 + 48 + 0 = 61$	 C150 $\begin{Bmatrix} 223 \\ 36 \\ 4 \end{Bmatrix}$ $39 + 48 + 3 = 90$	 C149 $\begin{Bmatrix} 217 \\ 35 \\ 4 \end{Bmatrix}$ $10 + 48 + 1 = 59$	 C154 $\begin{Bmatrix} 192 \\ 32 \\ 2 \end{Bmatrix}$ $12 + 45 + 13 = 70$	 C151 $\begin{Bmatrix} 207 \\ 33 \\ 4 \end{Bmatrix}$ $37 + 12 + 6 = 55$	 C155 $\begin{Bmatrix} 187 \\ 30 \\ 3 \end{Bmatrix}$ $0 + 0 + 1 = 1$
850°			 C202 $\begin{Bmatrix} 228 \\ 38 \\ 5 \end{Bmatrix}$ $20 + 48 + 4 = 72$	 C206 $\begin{Bmatrix} 202 \\ 31 \\ 4 \end{Bmatrix}$ $30 + 48 + 3 = 81$	 C203 $\begin{Bmatrix} 207 \\ 33 \\ 4 \end{Bmatrix}$ $18 + 48 + 10 = 76$	 C207 $\begin{Bmatrix} 183 \\ 29 \\ 4 \end{Bmatrix}$ $6 + 32 + 12 = 50$
900°			 C256 $\begin{Bmatrix} 269 \\ 42 \\ 6 \end{Bmatrix}$ $7 + 48 + 0 = 55$	 C260 $\begin{Bmatrix} 228 \\ 35 \\ 5 \end{Bmatrix}$ $8 + 48 + 2 = 58$	 C257 $\begin{Bmatrix} 226 \\ 36 \\ 6 \end{Bmatrix}$ $18 + 30 + 3 = 51$	 C261 $\begin{Bmatrix} 192 \\ 33 \\ 4 \end{Bmatrix}$ $3 + 48 + 6 = 57$

FIG. 28.

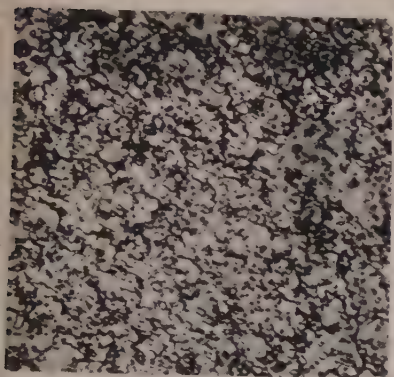
Test Cutters, all hardened by the same Standard process, made from blanks treated as shown.
 (For explanation of figures see Fig. 8, Plate VIII.)



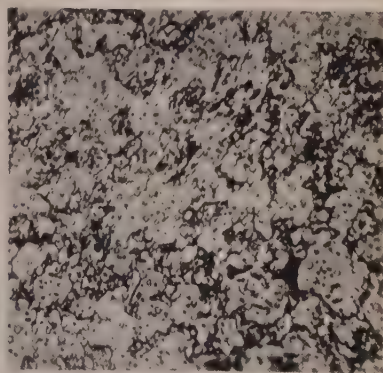
30



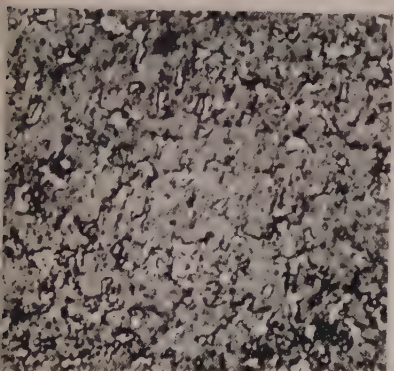
31



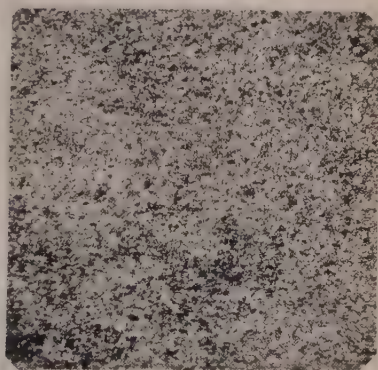
32



33



34



35

FIG. 30. B16. 1 hr. at 732° , water-quenched. $\times 500$.

FIG. 32. Same as Fig. 31. $\times 500$.

FIG. 34. B19. 12 hrs. at 732° , water-quenched. $\times 500$.

FIG. 31. B17. 4 hrs. at 732° , water-quenched. $\times 100$.

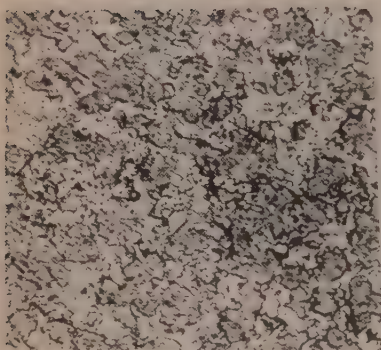
FIG. 33. B18. 8 hrs. at 732° , water-quenched. $\times 500$.

FIG. 35. B20. 16 hrs. at 732° , water-quenched. $\times 100$.



11

FIG. 11. B9a. 2 hrs. at 739° , water-quenched. $\times 500$.



36

FIG. 36. Same as Fig. 35. $\times 500$.
(Plate XIV).



37

FIG. 37. B22. 4 hrs. at 732° , sand-cooled. $\times 500$.



FIG. 38. B25. 16 hrs. at 732° , sand-cooled. $\times 500$.

to the cutters, and similar results emerged, for the sand-cooled bars which gave a high ratio usually corresponded with cutters which broke in hardening, the agreement between the two being as pronounced as the agreement between the blanks and cutters. It was naturally to be expected that the bars and blanks would, as stated above, be in agreement, when they were both sand-cooled after similar heat treatment, but the confirmation is valuable as showing that the relation holds good, and is repeated in an independent series, notwithstanding the margin of experimental error.

Further evidence may be obtained by examining the ratios of the water-quenched bars which correspond with cutters, and in this case the figures are more pronounced.

The Brinell-Shore ratios of the water-quenched bars corresponding to 66 cutters which showed a defectiveness of more than 50 were as follows :

Average ratio of 66 ¹ water-quenched bars	.	.	7.6
Highest " " " "	.	.	9.6
Lowest " " " "	.	.	5.9

The comparative figures for the water-quenched bars corresponding to 27 cutters which showed a defectiveness of less than 30 were as follows :

Average ratio of 27 water-quenched bars	.	.	6.3
Highest " " " "	.	.	7.6
Lowest " " " "	.	.	5.9

The following analysis from another standpoint is also of interest. Of 49 bars (water-quenched from heat treatment) with a Brinell-Shore ratio below 7,

24 corresponded with cutter defectiveness of over 50
25 " " " " under 30

but of 42 water-quenched bars with a ratio over 7,

40 corresponded with cutter defectiveness of over 50
2 " " " " under 30

The above indicates the agreement between a high Brinell-Shore ratio of a specimen water-quenched from heat treatment and

¹ The Brinell reading for nine of the bars was over 700, and in these cases the ratio has been calculated as for a figure of 700 only. If true Brinell figures had been procurable they would have given appreciably higher ratios for these nine bars, which all corresponded to cutters of high defectiveness. Bar B16a, which gave the very high ratio of 11.1 and corresponded with a cutter defectiveness of 74, has not been taken into account. If it were included it also would accentuate the case.

an increased liability of the corresponding sand-cooled steel to fracture on hardening. The figures also suggest that a low ratio affords no evidence either way. It may be stated, however, that a low ratio in the quenched specimen generally indicates that the steel will not crack on hardening, unless the low ratio is produced by instability due to short heats. The practical application of this would be to withdraw a specimen from an annealing heat at say 710° or 700° C. and, after quenching, to ascertain the Brinell-Shore ratio.

In the case of the bars which were hard on quenching after heat treatment (and which naturally corresponded with defective cutters) the high ratio may arise merely because the figures relate to a part of the hardness scale remote from the part which applies to the soft bars; and, in so far as this is the case, the difference in ratio may be capable of an explanation which is independent of any significance so far as hardening defectiveness is concerned. On the other hand, it need not be hastily assumed that the comparison between the ratios necessarily loses all significance when the figures are taken from remote parts of the scale, and in any case an examination of the figures shows that the same tendency is observable even when the hard bars are left out of account.

It is possible to pursue the matter still further, without reference to the cutters, by a consideration of the test-bars alone. As already noted, many of the test bars cracked around the hole in hardening, and the evidence afforded by the relation between these failures and the Brinell-Shore ratio after the previous heat treatment is on slightly different lines from the evidence of the blanks and cutters, because the shape of the bars was much less risky than that of the cutters; also the bars were machined before, and the cutters after, the heat treatment. The behaviour of the bars in this connection may be summarised as follows.

The following particulars relate to 95 sand-cooled bars. Of 30 bars (sand-cooled from heat-treatment) which cracked with the standard hardening:

7	had a ratio	¹ below	$6\frac{3}{4}$
23	"	"	above $6\frac{3}{4}$

¹ The ratio was, of course, obtained after sand-cooling and before standard hardening.

Of 65 bars (sand-cooled from heat treatment) which were sound after the standard hardening :

36 had a ratio¹ below $6\frac{3}{4}$
29 " " above $6\frac{3}{4}$

The following particulars relate to the 95 water-quenched bars corresponding to the above. Of the 30 bars (water-quenched from heat treatment) corresponding to the 30 sand-cooled bars which cracked with standard hardening :

13 had a ratio² below $7\frac{3}{4}$
17 " " above $7\frac{3}{4}$

Of the 65 bars (water-quenched from heat treatment) corresponding to the 65 sand-cooled bars which were sound after standard hardening :

55 had a ratio² below $7\frac{3}{4}$
10 " " above $7\frac{3}{4}$

The Brinell-Shore ratio of 95 sand-cooled bars and 95 water-quenched bars (190 bars in all) has been related above to the liability of the 95 sand-cooled bars to crack in hardening. It is seen that the evidence of both sets of bars is fairly consistent, and although the ratios gave no decisive indication as to whether the sand-cooled bars would crack or not in the subsequent hardening, yet it is apparent that a high ratio frequently went with liability to crack and a low ratio was usually associated with sound hardening.

It is understood that precise figures cannot be obtained for hardness, and that the margin of unavoidable error may seriously affect the Brinell-Shore ratio. Inasmuch, however, as this agreement between high ratio and hardening defectiveness persists over a considerable number of results, notwithstanding all the imperfections of material, treatment, and testing, it cannot be ignored and deserves further consideration.

APPENDIX VII.

IRREGULAR RESULTS AT 732° C.

Heating to 732° is referred to on p. 173. Some interesting results were obtained from bars which were water-quenched

¹ The ratio was, of course, obtained after sand-cooling and before standard hardening.

² The ratio was, of course, obtained after water-quenching and before standard hardening

from 732°, and before the standard hardening. In the first instance only three bars were treated, and the hardness results, which are plotted out in Fig. 10 (p. 174), were given as follows:

Bar B16a—732° for 1 hour—	Brinell 460—	Shore 41
„ B17a— „ „ 4 hours „	627— „	82
„ B19a— „ „ 12 „ „	418— „	62

The rise in hardness at four hours was disquieting; but an explanation was apparently forthcoming when the original recorder sheet was examined, and a note found to the effect that an accumulator was running down, and that after some hours a new one was connected up. The note in question, made on the day when the work was done, also stated that the error on this account was slight, and that the record was probably not more than a degree or two wrong. Such a rise in hardness would not have been expected unless the temperature had risen by something approaching half a dozen degrees; and if this had happened it was strange that B19a was not hard also, for it was in the furnace during the whole of the time when B17a was heating. In consequence of this discrepancy, five more bars were heated to 732° C. and quenched in water. The hardness results, as under, are also plotted out in Fig. 10 (p. 174).

Bar B16—732° for 1 hour—	Brinell 311—	Shore 50
„ B17— „ „ 4 hours „	321— „	50
„ B18— „ „ 8 „ „	311— „	51
„ B19— „ „ 12 „ „	514— „	85
„ B20— „ „ 16 „ „	321— „	50

In this series, B19 was hard after twelve hours' soaking, and there did not appear to be any irregularity in the treatment to account for such a discrepancy. In Fig. 29 the recorder sheet is reproduced showing that apparently the total variation in temperature was little more than a degree, and looking at the record it is difficult to see why B19 should be harder than B18 or B20. It may be that the change Acl.2.3 takes place in steps if sufficient time is allowed for the process, and that the hard bars were quenched during a transition. On the first occasion the change occurred in four hours, and when the experiment was repeated it occurred in twelve hours; but this may be accounted for by the fact that the temperature for the two series may have differed by 2° or 3° C. The first series was

heat-treated in March 1919 and the second in April 1920; and, as no more than the ordinary precautions were observed on each occasion, there may have been a slight difference in standardisation. Indeed there was independent evidence that such a difference had actually arisen.

In order to investigate further the behaviour of this steel on heating to 732° , Dr. Hatfield kindly had micrographs (Figs.

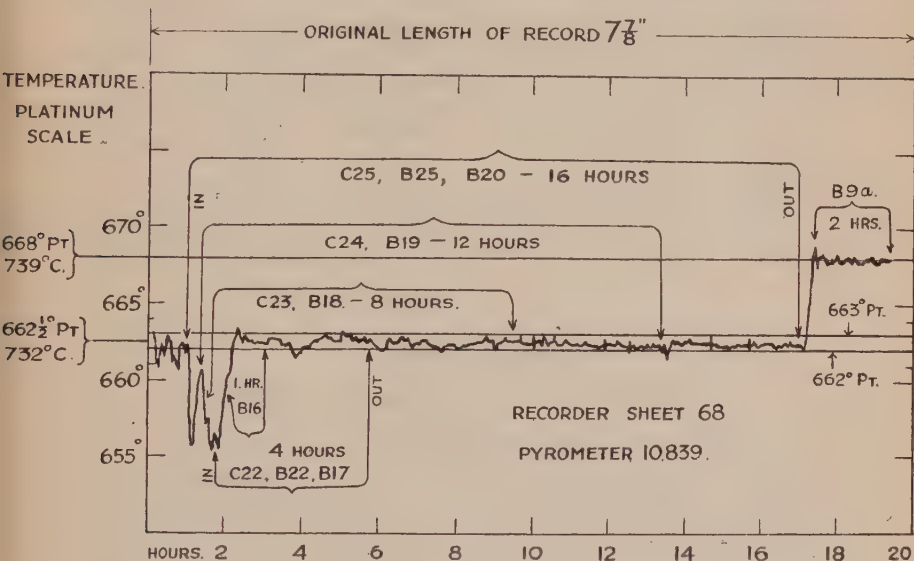


FIG. 29.

30 to 38, Plates XIV.-XV.) made from the seven bars¹ shown in Table XIV. Bars B17 and B20 show exactly the same Brinell and Shore hardness, but B17 corresponds with a cutter which broke badly on subsequent hardening, whereas B20 corresponds with a fairly good cutter. Dr. Hatfield observes that the only difference between these two bars (see Figs. 31, 32, 35, and 36) is increased homogeneity of B20, as shown in the two micrographs magnified 100 diameters; also there is approximately the same proportion of solid solution, but whereas B17 shows

¹ These bars, and bar B9a (making eight in all), were the only ones, out of the total of 262, which never underwent the standard hardening as the final process.

the usual banding B20 is practically uniform. The extra period of soaking may have caused migration of the segregated elements. The increased hardness of B19 is due to increased areas of solid solution. (See Fig. 34.)

TABLE XIV.—*Test Bars Heat-treated as Shown, and not Subjected to Standard Hardening.*

Reference Number of Bar.	Micrograph Fig. Number.	Time in Furnace at 732° C. (Hours).	Method of Cooling.	Hardness.	
				Brinell.	Shore.
B16	30	1	Water	311	50
B17	31, 32	4	"	321	50
B18	33	8	"	311	51
B19	34	12	"	514	85
B20	35, 36	16	"	321	50
B22	37	4	Sand	217	35
B25	38	16	"	217	35

APPENDIX VIII.

CRACKING OF TEST BARS IN RELATION TO DEFECTIVENESS OF TEST CUTTERS.

Table IX. (p. 178) shows the defectiveness of cutters that had been raised to 750° C. in the first furnace for heat treatment, and the letters "S" and "C" show whether the corresponding sand-cooled bars were sound or cracked on hardening. It will be seen that only one bar was cracked, which indicates that the temperature of 750° in the heat treatment was favourable for the prevention of hardening cracks, and the bad cracking of most of the cutters was simply due to the extreme difficulty (according to intention) of hardening such pieces. The behaviour of the bars and cutters shown throughout the table was reasonably consistent, except that cutter 750°-725°-1 hour was expected to have a defectiveness of more than 50 instead of only 23.

Table X. (p. 179) relates to cutters that were raised to 800° in the heat treatment, and shows that nearly half of the corresponding sand-cooled bars cracked on hardening. The results from the bars and cutters taken together are consistent, except

that two bars (800° - 732° -1 hour and 800° - 706° -1 hour) were both sound, whereas they were expected to crack.

Table XI. (p. 180) has reference to pieces that underwent a temperature of 850° in the heat treatment, and shows that six bars out of nineteen cracked in hardening, which is a better proportion than was obtained from the 800° bars shown on Table X.; and although the number of bars in the series is too small to warrant the drawing of conclusions, the results in question are not inconsistent with experience of this kind of steel. The results in Table XI. are consistent, except that bar 850° - 725° -4 hours was cracked contrary to expectation, and that the defectiveness of cutter 850° - 718° -12 hours, which was actually 38, should have been less than 10.

In Table XII. (p. 181) the high temperature in the heat treatment was 900° . Nearly half of the bars cracked, and the results from both bars and cutters were remarkably consistent.

APPENDIX IX.

VARIATION OF TEMPERATURE AT 725° C.

Second furnace temperatures of 725° are referred to on p. 187. According to Fig. 21, p. 190, the bars heated to 850° or 900° changed at 725° more readily than those which had been heated to only 750° or 800° . This is contrary to experience, and is doubtless explained by an irregularity that was noted during the 725° soaking which followed the 750° and 800° heats. At the time, however, it was not thought that an error exceeding 1° or 2° had arisen, but the results suggest that the temperature (725°) was fully 3° too high. Bar B70, 750° - 725° -16 hours, was treated, as already noted, nearly a year after the other bars in this series, and the figures seem to indicate that the 725° standardisation for this bar differed from the previous corresponding standardisation, but agreed with the 725° standardisation for the 850° and 900° bars.

Cutter C69 (750° - 725° -12 hours, see Fig. 22, Plate XI.) was badly broken, the defectiveness, by a coincidence, being 69. This tallies remarkably with the slow recalescence of the bars shown in Fig. 21, and commented on above. The blank C69 was, however,

heat-treated at the same time as the corresponding bar, so that the cutter result does not corroborate the bar result as regards its relationship to the 850° and 900° bars ; but it does show that the two results consistently go together, and if any mistake arose the effect is equally apparent in bars and cutters. The behaviour of cutter C70 (750° - 725° -16 hours, Fig. 22) is also strikingly in full accord with the corresponding bar shown in Fig. 21, and referred to above.

DISCUSSION.

Dr. W. H. HATFIELD (Sheffield) said he had had the opportunity of following the work during its progress. The hardening of a complicated form of article such as that dealt with in the paper was a difficult matter, and had to be accomplished in such a way that cracking was avoided. It was undoubtedly difficult theoretically to explain why the changes in the process of heat treatment should have such a definite effect in the elimination of cracks. The work would probably stimulate further investigations of a similar nature on other steels, and perhaps ultimately a mass of practical data might be arrived at which would enable a previous heating to be interposed before the actual hardening heating, and much serious trouble encountered in some machine tool works would be eliminated. It was a very important fact that the Shore value did not maintain a definite ratio to the Brinell value. The Shore scleroscope and the Brinell ball test were the two means of testing the hard conditions of steel. The Brinell rather failed for very hard conditions, and only the Shore scleroscope remained available. The mechanism of those two methods of testing had to be exactly understood.

Professor J. O. ARNOLD (London) said he was in rather a difficult position. In the past Mr. Brayshaw and he had done some good work together on the hardening of steel, and Mr. Brayshaw had designed for him furnaces which were working beautifully in the University of Sheffield. Mr. Brayshaw had referred to the title of his paper—"Tungsten Tool Steel." The title was a misnomer; 0.8 per cent. of tungsten did not constitute tungsten steel. Professor Read of the University of Wales and he (Professor Arnold) had done a lot of work on tungsten steel, in which they had taken every type from 2.5 up to 20 per cent. Had Mr. Brayshaw read that paper he would have seen it worked out in a constitutional formula what an exceedingly small relative effect 0.8 per cent. of tungsten could have on ordinary carbon steel. There was only one molecule of tungsten carbide to fifteen molecules of iron carbide in that steel, and its effect might almost be neglected. A really genuine tungsten steel would contain 1.2 per cent. of carbon and 3 per cent. of tungsten. Such a steel was what he had always used for drilling very hard white iron for analysis. To attempt to drill with such a steel as Mr. Brayshaw's "tungsten steel" would be impossible. He was glad that Mr. Brayshaw had recognised the facts and agreed to a correction in his title.

To the majority of engineers very often a piece of steel was simply a piece of steel; but the varieties of steel were so enormous that that was a generalisation which no metallurgist could possibly accept.

The total impurities in Mr. Brayshaw's steel—tungsten, chromium, and manganese—amounted to 1.33 altogether. That greatly influenced the recalescence. Mr. Brayshaw had found that Ar1.2.3 occurred 18° higher than in a pure carbon steel (7140° C.). That was of interest. He agreed with Mr. Brayshaw when he said that the change in a steel—he would not call it tungsten steel, but a steel containing tungsten—was not complete at the temperature Mr. Brayshaw had specified. Had Mr. Brayshaw referred to the work on the subject by Professor Read and himself, he would have known that the change of carbide of tungsten was not completed until 1100° C. Why Mr. Brayshaw had baked and boiled those unfortunate bars and cutters in the way he had done to get information for metallurgical work, he could not understand.

He was glad to notice that Mr. Brayshaw frankly admitted having been unable to estimate the effect on his results of original sin in the steel—always an extremely important factor. Anyone engaged with tool steel knew that, with exactly the same treatment carried out with the greatest care, it was often possible to get strangely discordant results from the same bar. In connection with the milling, turning, and drilling duty of tool steel, Brinell figures were absolutely useless. He would take the extreme case he had met with in his researches on the influence of the Brinell test as compared with the actual working of the steel. That was in an ordinary plain carbon steel containing about 1½ per cent. of carbon, hardened. The Brinell hardness was in the vicinity of 700. He had then taken a high-speed steel with a Brinell hardness in the vicinity of 600. Taking those results, the 700 should have been a better steel than the 600. In the result, however, the value of the Brinell test for tool purposes was completely swept away. The carbon steel which had stood 700 Brinell had lasted, under the conditions they were working on the lathe, half a second. The high-speed steel had run for sixteen minutes, and for four of those minutes it had been running at a red heat of about 650° to 700° C. If the drilling results, the milling results, and the lathe results were compared with a Brinell test, it would be found there was practically no correlation whatever in the work done by the steel.

Mr. H. BREARLEY (Sheffield) said he had hoped that Mr. Brayshaw would focus attention on some rule—some brief rule probably—which an observant hardener could follow in shop practice in order to produce tools with the great probability that they would not crack. The fact that the steel used contained only 0.8 per cent. tungsten and therefore could not properly be regarded as a tungsten steel had been commented upon. In his opinion the addition of 0.8 per cent. tungsten did exert a very important influence on carbon tool steels. It might not be a very important scientific influence or a very important physical influence, but it was a very important commercial influence. Perhaps there was no class of craftsman in the world who were so sensitive

about the quality of their work as steel hardeners. One of the means whereby a steel hardener acquired merit was the appearance of the fractured surface, if perchance in the hardening operation or in use a tool which he had hardened fractured. If that tool fractured with a beautifully fine surface, like the tools of Mr. Brayshaw, the hardener was very pleased with himself; and other people with divergent views found it very difficult indeed to make a good case against the hardener when there was under their eyes a beautifully smooth fracture such as the addition of even $\frac{1}{2}$ per cent. of tungsten would give to ordinary carbon steels. Whether there was any technical or physical advantage in adding tungsten to ordinary tool steel or not, tool steel-makers who had difficulties with hardeners to contend with would find it advantageous to add a bit of tungsten.

Mr. Brayshaw had evidently been at very considerable pains to produce the various specimens, which had been through the different heat treatments, so as to be strictly comparable. The amount of right-down hard work involved in the paper was simply overwhelming. He admired Mr. Brayshaw's courage for tackling a job of such a sort. That was why he was very anxious to get the real kernel of the paper, if possible, in some form of rule or observation that could be applied in ordinary workshop practice. There were two things he thought Mr. Brayshaw had rather omitted which might have very considerable influence on some of the results he had obtained. Mr. Brayshaw's original material had consisted of two ingots, one of which he had made into cutters and the other he had made into his test-bars. Mr. Brayshaw did not state what kind of ingots they were, nor did he state how the bars were forged. Anybody who had had much to do with tool steel knew that one might get a bar one end of which was not at all like the other, owing to want of uniformity in reheating the billet or bloom or ingot from which the bar was made. He thought it might have been instructive had Mr. Brayshaw actually nicked the bars and fractured them, so as to satisfy himself that they had been either forged or rolled, as the case might be, in a manner which, whether good or bad, had at least been uniform. Again, it was well known that the physical properties of an ingot were not the same throughout. The bottom third of an ingot and the top fourth of an ingot, however the material was cast, were physically different to the material right out of the middle, and he thought it would have been better, considering the immense amount of work Mr. Brayshaw had put into his subject, if he had started out with what he (Mr. Brearley) called filleted billets—that was to say, if he had taken an ingot, made it into a slab, cut out the centre, and then had used the two sides of the material. At any rate, he made that suggestion to Mr. Brayshaw as being one that would produce not perhaps absolutely uniform material but more uniform material than he was likely to obtain by simply forging or rolling down an ingot.

There was another point with respect to uniformity which was

not specifically mentioned. Mr. Brayshaw did specifically state what precautions had been taken to obtain certain dimensions in his cutters, and so on, which were strictly comparable throughout. So far as machining was concerned, there was something rather more important than faultless dimensions, and that was the condition of the machined surface. It was well known that if certain kinds of tools, say reamers, were made, and one flute of a reamer happened to be milled with a cutter that had got dull, it became impossible to harden that reamer and make a sound job of it. He noticed that after each eighth cutter had been made the milling cutter used in milling them had to be sharpened, so that the eighth cutter was obviously not, so far as the condition of the surface was concerned, quite the same as the first cutter. He would be glad if Mr. Brayshaw would state what was the eutectoid composition of a steel containing 1 per cent. tungsten, and also whether he had determined the temperature at which the free carbide of his 1.14 per cent. carbon steel went completely into solution.

The point was important and fundamental, so far as the planning and carrying out of work of the kind under discussion was concerned. He assumed Mr. Brayshaw had made such determinations before he started.

Mr. BRAYSHAW said he had normalised at 825.

Mr. BREARLEY, continuing, said Mr. Brayshaw was a very ardent admirer of salt baths, and so was he; but there was one defect in a salt bath, namely, that an object could not be put into a salt bath at a temperature below the fusing point of the salt. A salt bath must be fluid, so that if a complicated tool were placed in a salt bath it was being put into a heated area which was pretty hot. Makers of very delicate tools had told him—he was not now speaking from experience on that particular point—that they were able, by prolonging the heating period to as much as ten hours, that was to say, by packing tools in a cold furnace and allowing them to heat up very slowly indeed through eight or ten hours, to produce results that they could not possibly produce when the tools were put into a heated furnace, whether it were a salt bath or any other type of furnace. As was well known, during the heating period a point was reached where the gradually expanding steel object somewhat suddenly contracted, and when that period was reached at different times by different parts of a complicated object like a cutter, volume changes and strains could occur which might ultimately have a good deal to do with the breakage of the tools. At any rate, experiences related to him by very well-known tool makers rather suggested there was a great advantage in heating up a fragile tool steel object very slowly, which in a salt bath could not be done.

Dr. HARTLEY (Warrington) said contributions such as that of Mr. Brayshaw were of especial interest to those who like himself were

concerned with the question of the design of furnaces for metallurgical purposes.

It would be of interest if Mr. Brayshaw would give some details of the construction of the salt-bath furnaces, and especially the mode of burning the gas which he employed, and state whether any thermostatic control was used, in connection with the prolonged second heats of his preliminary treatments.

It was no mean achievement to maintain, with an industrial furnace, a temperature of $732^{\circ}\text{C.} + 1^{\circ}\text{C.}$ over a period of sixteen hours. The result was emphasised by the fact that the record sheet, Fig. 29, given was reproduced in connection with his discussion of abnormal Brinell-Shore figures obtained for his test-bar B 19, and was presumably an average and not selected to illustrate the furnace possibilities.

He (Dr. Hartley) would like some information as to the pot life obtained, and also as to Mr. Brayshaw's experience as to the influence of the mode of heating on the resulting life. For temperatures of 750°C. and upwards he recommended a nickel-chromium pot, and a cast-iron pot for lower temperatures. If he (Dr. Hartley) interpreted him aright, when using the steel that he had examined he would require temperatures of 750°C. and 718°C. Which type of pot did he propose to use? It would also be of interest to know his views on the relative merits of the steel pot demanded by some salt bath users.

The paper emphasised the importance of temperature uniformity and control in hardening furnaces, and it would seem to follow as a corollary that in those cases where salt-bath heating was not adopted it was of primary importance to ensure that there should be no direct impingement of the burning gases on portions of the tool or cutter being heated. Had Mr. Brayshaw examined any of his blanks or bars with a view to discovering whether decarburisation had occurred to any appreciable extent, especially after the first treatments at the higher temperatures before they were ground for the purpose of the physical tests?

Whilst at first sight it might appear that immersion in a molten salt would be the ideal means of heating a cutter of finished size for hardening purposes and avoiding decarburisation, trouble was at times experienced, especially in high-speed steel hardening, owing to the unsatisfactory wetting of the surface of the metal by the molten salt. That was overcome by the use of two baths, a lower temperature one of suitable composition to ensure wetting after immersion, from which the tool was transferred to the high temperature bath and the treatment completed. Had Mr. Brayshaw experienced any trouble on that score either in the present research or in his previous work?

Further, had he at any time experimented to determine the extent to which the unsatisfactory results obtained after the first treatment at the higher temperatures, such as 900°C. , were due to the somewhat drastic temperature changes to which those particular specimens were submitted? Would not the procedure of plunging the cold blanks

and cutters into the hot salt bath introduce disturbances which might not occur if the specimens had been preheated previously. Apart from the question of the actual constitutional changes, it should not be overlooked that the physical treatment to which the specimen was subjected when suddenly immersed in a bath at 900°C . was very drastic as compared with that of a similar specimen immersed in a bath at 750°C . with the steel showing a heating arrest at 738°C . In that connection he (Dr. Hartley) referred to the rate of change of temperature in the various cases as mentioned in Appendix II., on p. 205. He was not quite clear from the summary whether Mr. Brayshaw believed that he could omit the preliminary treatment at 750°C . and give only the prolonged treatment at 718°C . in the case of his particular steel. The most satisfactory hardening would appear to be obtained by a similar two-stage heating, or rather cooling, prior to the quenching procedure—a process which he (Dr. Hartley) believed was in use in some works.

Mr. R. S. WHIPPLE (Cambridge) said it was often stated that English firms did not carry out research work, and that it was being left to American organisations to run private laboratories and to carry out work which involved heavy expenditure spread over a long period of time. On that ground alone he thought Mr. Brayshaw should be warmly congratulated for having undertaken such a piece of work as that described in his paper.

He had been interested in the measurement of temperature for many years, and had known something of the work which Mr. Brayshaw had carried out in that connection. He was particularly interested in the record that Dr. Hartley had referred to on p. 213. That appeared to show that a stage further had been reached in temperature measurement. In the old days they trusted entirely to the judgment of the experienced hardener. Later on it was found that the alloy steels required more accurate control, and the pyrometer was introduced into industry to control the temperatures. He thought the stage was now reached when a still further step had to be taken: the human element cut out almost entirely and automatic temperature control adopted. In the United States some firms had introduced automatic methods of controlling furnace temperatures to a fairly high accuracy.

If possible, it was always well to have standards of reference, and Mr. Brayshaw's suggestion of a standard for a hardness test might come into use if a standard steel existed, as Professor Arnold had pointed out. He (Mr. Whipple) wondered whether it would be possible for a standard steel to be produced by some steel manufacturer under the control or advice of the National Physical Laboratory, working in conjunction with the Iron and Steel Institute, from which standard bars of steel could be made and carefully tested at the National Physical Laboratory in the manner suggested by Mr. Brearley. From those bars, which should be tested at intervals throughout their lengths,

small discs could be cut and provided by the National Physical Laboratory. They could be supplied at a moderate expense, and might yield comparative results between various methods of hardening and treatment which would be of service. If such discs could have been used throughout Mr. Brayshaw's research, it might have been possible for someone else to carry on the investigation and to link up his work by such discs, so that the new results would be strictly comparable with those of Mr. Brayshaw.

Professor TURNER (Birmingham) thought that the causes of hardening cracks might be considered under two heads: ultimate and proximate. The proximate causes were, first, that a very hard material which was brittle was produced; and, secondly, a volume change occurred which, with a brittle material, naturally tended to produce cracks. Mr. Brayshaw had given some account of the change of length of the bar, and he (Professor Turner) assumed that that was intended as some indication of the volume change. To take the length of a bar under those conditions did not, however, give an accurate indication of the volume change. The volume changes which took place during the experiments of Mr. Brayshaw were in effect those of an ordinary carbon steel. The subject was examined by Professor Langley some years ago, and his results might be summarised as follows:

The higher the proportion of carbon and the higher the temperature from which quenching took place, the greater was the volume change; and

That volume change was determined by means of careful specific gravity tests.

He had recently seen an interesting sample of a bar of steel which had been repeatedly heated and cooled, probably 500 times at least, shown by Mr. Weeks of Barrow. That had not been done for the purpose of making a tool but for other purposes; as a matter of fact, it had been done by the workmen with the object of heating some water. The result had been that the steel shortened very much and had tended to become spherical, nearly the shape of a cricket-ball, except that the ridges still remained from the original edges and corners of the bar. Evidently therefore the expansion which resulted from rapid cooling, and the contraction which occurred at a certain temperature on reheating, did not occur uniformly in all directions in a bar or in a tool. The natural tendency appeared to be to shorten in the direction of length and to widen the bar. Incidentally he needed scarcely to emphasise the fact that the only way to ascertain the volume change was by determining the specific gravity, so as to know the change in the whole mass of the metal.

With regard to hardening, it was to be recognised that if machining tests were being dealt with, or even the wear of a tool, those properties could not be determined merely by ascertaining the hardness of the

material; hardness and machinability, for example, were different properties. They did not necessarily follow in the same order. If, for example, a homogeneous material like mild steel were taken it would be found that the hardness and the tenacity and certain other properties would follow in a regular order with the increase of carbon; but with a material that was specially hard or specially soft hardness no longer was an index to its working property. A familiar example was the case of a piece of soft copper, from which it would be found an extremely slow process to turn off a quantity of material. What happened, he thought, in connection with the hardening of steel, when a certain best hardness, or temperature of hardening, was exceeded, was a tendency for it to become more coarsely crystalline. The effect of a heterogeneous material was attained, and it could not be expected that the Shore scleroscope acting upon a very small part of the material would give the same results as a Brinell test, which acted upon a relatively larger quantity and took in, to some extent, both the hard and the soft together. In those circumstances a difference was to be expected. It might be remembered that some years ago he had given the figure of 6 as being the approximate ratio. It had been shown by Mr. Shore that for the brass alloys a number of samples gave a ratio as low as about 4.5, and he believed that those were good turning alloys. In Mr. Brayshaw's experiments there were ratios even higher than 8, and in those cases there was a material which was brittle. That was only what might naturally be anticipated from their knowledge of the character of the two tests which were under consideration.

Mr. W. C. HOTHERSALL drew attention to the effect of excessive surface decarburisation. In the treatment prior to quenching, if excessive surface decarburisation occurred there was a tendency for the steel in the centre of the material, which had a higher carbon content than that near the outside, to expand more on hardening than the outside layers. The result was that on quenching cracks might occur. He had carried out some experiments on 3 per cent. tungsten, 1 per cent. carbon steel. The specimens were in the form of cylinders about $\frac{1}{2}$ inch in diameter and $1\frac{1}{2}$ inches in length. The cylinders were heated to various temperatures as follows:

Steel: 3 per cent. Tungsten, 1 per cent. Carbon. Specimens quenched vertically in water at 20° C.

Specimens heated to . . .	790° C. ¹	830° C. ¹	900° C. ¹
„ quenched from . . .	790° C.	830° C.	800° C.
Number treated	90	90	60
Number cracked on hardening . . .	0	3	47
Number cracked when covered with charcoal (other conditions the same)	0	0	

¹ For twenty minutes in each case.

He thought those results afforded some support to the suggestion that in some cases at least the effect of surface decarburisation and the consequent differential expansion of the interior and surface on hardening might be an important factor in causing quenching cracks.

CORRESPONDENCE.

Dr. A. McWILLIAM (Sheffield) wrote that he congratulated Mr. Brayshaw on his success in finding a practicable heat treatment that resulted in the reduction to a minimum of hardening cracks in complicated designs of milling cutters; and on the fact that he, a milling cutter manufacturer, had given the details of the successful process he had evolved, information that was generally withheld as of the nature of a trade secret.

He (Dr. McWilliam) had done a considerable amount of work on hardening and tempering apart from the various series published by McWilliam and Barnes, which were all done, in the possible ranges, in two of Mr. Brayshaw's salt-bath furnaces, and he had gradually been impressed with what he came to regard as a fact, that the condition of the steel as to former heat treatment was of great importance, although one would have thought that the heating before hardening would have neutralised most ordinary heat treatment effects. He thought Mr. Brayshaw had shown clearly that the heat treatment before hardening was of the greatest importance and had found what that previous heat treatment should be.

It was remarkable that the flaws in seventeen cutter blanks, some slight and some very bad, had no effect on the cutters on hardening.

Had Mr. Brayshaw proved in any way that the cementite had gone into solution at 825°C ., as suggested under normalising on p. 148, or was the statement just made casually? The experiments, taken in conjunction with the results given in a former paper, threw much light on the change points $\text{Ac}1.2.3$ and $\text{Ar}1.2.3$.

In a paper published in the *Journal of the Iron and Steel Institute*, 1915, No. I., McWilliam and Barnes had shown that the Brinell test gave a measure of the tenacity of steel, and the Shore test no doubt gave a measure of elasticity, so it would appear that when the proportion of the tenacity of the steel in the blanks to their elasticity was high the cutters made from those blanks were liable to hardening cracks.

Probably the most interesting and important statement was that for a steel giving in the ordinary way an $\text{Ac}1.2.3$ point at 738°C ., "Apparently there is a range of temperature somewhere about 715°C . to 725°C . within which, with prolonged soaking, the steel reaches a condition in which the liability to hardening cracks is reduced to a minimum."

Professor S. REJTÖ (Budapest) wrote that it was most important that the advancement of science should be supported and confirmed by a great number of practical experiments, therefore Mr. Brayshaw's numerous experiments were of great value as confirming results which were obtained before by theoretical work. The experiments had more claim to interest as they dealt with a material with a high sulphur and phosphorus content, and tools made out of such material would crack in great percentage. Sulphides at 298°C . were diminishing and about 138°C . increasing in volume, and that volume change in a brittle material caused cracks. In his (Professor Rejtö's) "Mechanical Technology," printed in Hungarian, he published his theory by which the mechanical properties of the special steels could be calculated from the composition of the iron alloys if they were fully annealed. As to the conclusions in many of them he was in full agreement, but there were some points to be discussed.

In regard to the change of length after heat treatment but before hardening it was stated that the bars heated to 900°C . and then quenched, lengthened noticeably, those heated to 850°C . only a little, and those heated to 800°C . and 750°C . shortened. The first two facts agreed with the present standpoint of the science but not the two last.

The bending tests showed worse and worse results as the temperature of the heat treatment rose from 750° to 900°C . That was because steels heated in the austenitic region showed an enlargement of their grains which were greater the longer the heating lasted and the higher the temperature. The bad results at 900° were explicable by the fact that that temperature lay near the solidus of the tungsten steels and therefore oxidation could take place.

That the Brinell hardness after hardening was in all cases nearly constant (above 700) showed that the mechanical properties of the steel depended on the last heat treatment, supposing it lasted long enough, on the temperature.

As to the high Brinell-Shore ratio of the most cracked cutters, correctly treated steels should have a minimum Brinell-Shore ratio, as the experiments showed, but in the case of minute cracks the Brinell number remained a maximum whilst the Shore number decreased because the cracks impaired the elastic properties.

As to the results of Brinell tests of bars and blanks heat treated near and above the allotropic change, Professor Howe showed that the best results in hardening could be obtained by heating the specimen 50° to 100°C . above the change point. Below that temperature a little pearlite remained in its original state and made the tools softer. That those bars heated to only 725°C . (that was below the critical point) were hard, reinforced Mr. Brayshaw's assumption that the allotropic change did not occur at one temperature but in steps, although it would be inexplicable that 706°C . should again confer great hardness.

Professor H. C. H. CARPENTER, F.R.S. (Royal School of Mines), wrote that he had been especially struck with Mr. Brayshaw's sugges-

tion, based on his experiments, that the changes Acl.2.3 and Ar3.2.1 might take place in steps and that definite stages corresponding with certain temperatures might be reached, provided sufficient time was allowed. Mr. Brayshaw inferred that there was a range of temperature from about 715° to 725° within which, after prolonged heating, the steel reached a condition in which the liability to hardening cracks was reduced to a minimum. That was a very important conclusion.

With regard to the suggestion of a transformation by steps at the A1 change, according to the equilibrium diagram there was a single temperature, generally taken to be about 720°, at which austenite passed into pearlite on cooling and pearlite reverted to austenite on heating in a eutectoid steel. In conformity with all other workers, however, Mr. Brayshaw found the change to take place at a higher temperature on heating than on cooling, even with slow rates of change, the difference in temperature being about 20°. It was important to realise that the austenite to pearlite inversion really involved two changes, namely, the conversion of γ to α iron and the precipitation of cementite from solution. That at once indicated the possibility of an inversion by steps such as was suggested by Mr. Brayshaw. Moreover, in 1919, Professor K. Honda¹ put forward the view that the so-called A1 transformation was not single but compound and consisted of:



Each of these constituents had a characteristic specific gravity, austenite having the highest and martensite the lowest density. Hence the Ar1 change in the steel produced an expansion, which was a differential effect of the expansion due to the austenite to martensite inversion and the contraction due to the martensite to pearlite inversion. In quenching experiments the rates of cooling in the outer and inner portions of a steel specimen differed considerably from each other. In the outer portion, where the cooling was very rapid, the martensite to pearlite change was prevented, and even the austenite to martensite change was only partial, so that the metal contained austenite mixed with martensite. In the inner portion, however, where the rate of cooling was slower, the austenite might be completely changed to martensite, but the further transformation to pearlite was prevented. It appeared to him (Professor Carpenter) that other evidence existed besides that contained in Mr. Brayshaw's paper, indicating the possible step-like nature of the Acl and Ar1 transformations, and he considered that further research on that matter was called for and, if undertaken, would throw considerable light on the important practical results obtained by Mr. Brayshaw. The results might quite conceivably affect the form of the equilibrium diagram.

¹ *Science Reports*, vol. viii. p. 181.

Sir ROBERT HADFIELD, Bart., Past-President, wrote that he had read with much interest Mr. Brayshaw's paper with regard to "The Prevention of Hardening Cracks and the Effect of Controlling Recalescence in a Tool Steel." As a research of that kind had an important practical bearing, it seemed to him the Institute was indebted to Mr. Brayshaw for the manner in which he had come forward and placed important data before the members. Such work deserved encouragement rather than what might be termed ordinary criticism. In another paper which Mr. Brayshaw read before the Institution of Mechanical Engineers in April 1910, on "The Hardening of Carbon and Low Tungsten Tool Steels," a portion of that was a joint research with himself. The data then obtained were found of considerable service, and he believed they would also be useful in the present instance.

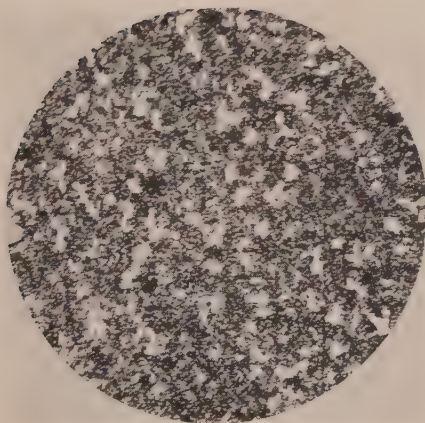
The tensile strength calculated from the bending test on specimen B10, 196 tons per square inch, was a remarkable result, and showed what could be done with the careful attention Mr. Brayshaw gave in his experiments. He (Sir R. Hadfield) hoped that he would continue his researches, feeling sure that the practical man would find in them valuable knowledge.

Mr. P. B. HENSHAW (Sheffield) wrote that it was quite evident that great difficulty would be experienced in arriving at the relative figure of defectiveness in the hardened cutters. The hardening of the test-bars and cutters seemed to be unsatisfactory. If it were desired to produce cracking the method adopted would be quite satisfactory, only the defects would not be produced by the heat treatment the steel had received, but by the method of hardening.

The results would have been much more valuable had a better method of hardening been adopted. The time taken for the actual quenching was much too short and the bars and cutters were taken out of the water far too soon. As the form of cutter was a difficult one to harden correctly, that should have served the purpose of testing the effect of the various treatments without introducing other variations certain to be produced by an undesirable quenching method.

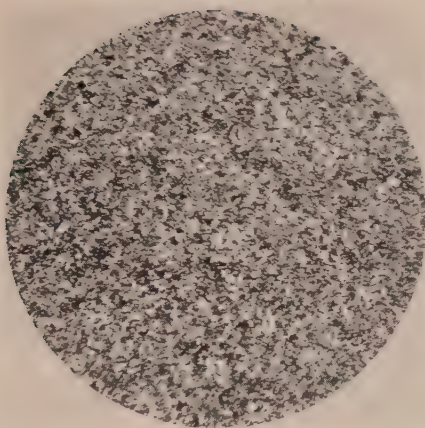
The heating and cooling curve on the 2½ inches diameter bars obtained on a Callendar recorder confirmed the result obtained by Mr. Brayshaw, the Ac3.2.1 point being 740° C. and the Ar3.2.1 point at 713° C. on cooling from 920° C. A differential curve obtained by the Saladin apparatus on the smaller section of steel was shown in Fig. A, the Ac3.2.1 being 740° C. and the Ar3.2.1 at 710° C. cooling from 935° C. It would be noted that a further point showed up on the cooling curve at 682° C. A corresponding point was also shown on the dilatometer curve.

Photomicrograph No. 1 (Plate XVA.) showed the structure of the steel, which had been cooled down from 780° C. then quenched out at 690° in water. Photomicrograph No. 2 showed a steel quenched at 665° C., i.e., after point of 682° C. had been passed. The white con-



No. 1.

Formalized at 910° C. in air. Heated to 780° C., cooled in furnace to 690° C. over 12 minutes, held at 690° C. for 5 minutes and quenched in water. Etched 2% picric acid in alcohol for 30 seconds. $\times 125$



No. 2.

As Fig. 1, but cooled to 665° C. over 15 minutes, held at 665° C. for 5 minutes and quenched in water.

stituent was undoubtedly ferrite. Both pieces had previously been normalised by cooling from 910°C . in air. The time allowed for soaking at the quenching temperature was five to seven minutes. If that period was prolonged to twenty minutes the structure of

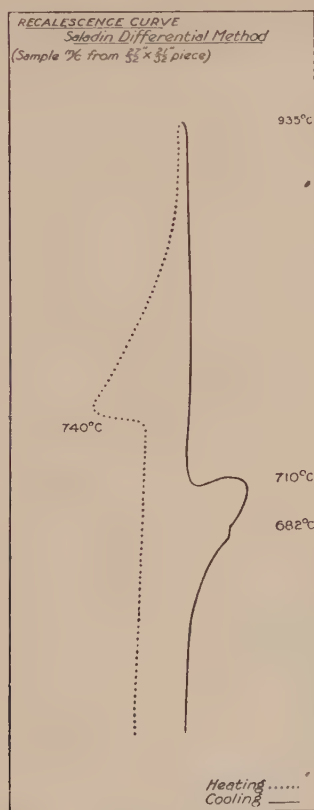


FIG. A.

the specimen quenched at 690°C . approximated to that shown in photomicrograph No. 2.

The curves shown in Fig. B (p. 230) were obtained on the steel used by Mr. Brayshaw by means of a dilatometer similar in principle to that described by Andrew, Rippon, and Miller.¹ The size of the test-pieces used was 2 inches long, $\frac{1}{8}\frac{1}{2}$ inch diameter, with a $\frac{1}{16}\frac{1}{4}$ inch hole through the centre.

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 527.

Dr. SCHWINNING (Dresden) wrote that the researches of Mr. Brayshaw were of value in ascertaining the causes of and modes of averting hardening cracks in tool steel. Such cracks were always tension cracks. All causes which increased tension or diminished the resistance of the

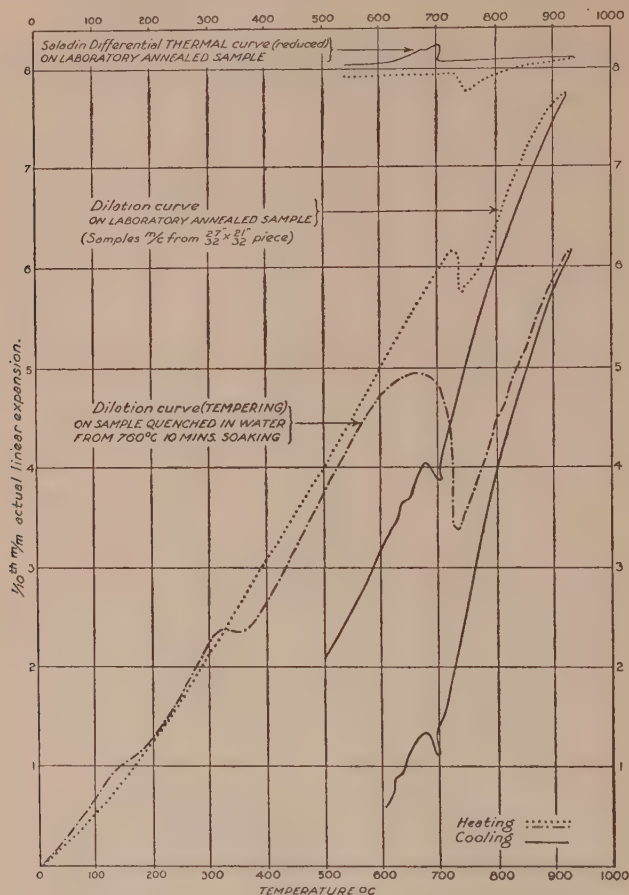


FIG. B.

material contributed to the appearance of hardening cracks. The most important causes were: The shape of the piece to be hardened (irregular cross section, grooves, &c.); the material qualities of the steel (flaws; too high coefficient for heat expansion); the heat treatment and crystalline structure previous to quenching (faults in forging, uneven annealing, irregular distribution of cementite, &c.); the mode

of heating for hardening; the maximum hardening temperature, and lastly the mode of quenching which had to be suitable to the piece to be quenched. Mr. Brayshaw had tried to elucidate the influence of heat treatment previous to hardening, a subject hitherto insufficiently studied, and had reached extremely interesting results which were very important from the practical point of view. By annealing all traces of uneven structure, derived mostly from the previous forging, had to be eliminated and very even distribution of the cementite must be striven for. The most perfect method of heating was in the salt bath with correct temperature control. To examine the stress and toughness of hardened steel he (Dr. Schwinning) used two hardened balls, slightly covered with soot, pressed against each other. After the pressure had been applied the diameter of the pressure surface, which was quite clearly seen on the thin soot covering, could be ascertained by a micrometer. For hardened steel the best test was perhaps the pressure at which the first crack appeared on the hardened surface. That first crack was circular, surrounding the pressure surface. It appeared at pressures which were much below the breaking stress and were not always in proportion to the breaking pressure of the ball, but it was clear that that pressure, corresponding with the first appearance of a crack, was a measure of the toughness of the hardened steel. The toughness thus ascertained was dependent on the method of hardening in so far as it diminished rapidly when the best possible interval of hardening temperature was exceeded. The toughness was likewise dependent on the duration and method of heating to the final hardening temperature. It was less known that when the most favourable limit of hardening temperature was exceeded (and that limit was very small for carbon steel and somewhat larger for chrome steel), not only the toughness but also the hardness was decreased. The unavoidable tensions due to hardening led to cracks as the toughness diminished.

Mr. J. NEILL GREENWOOD (Stocksbridge) wrote that the results of the preliminary treatments on bars were much more important than the necessarily erratic results from the standard hardening of the complicated cutter described. That type of cutter did not give even a good treatment a fair chance, and with bad treatment the cutters were so broken up as to make it very difficult to assess their badness. Bearing in mind the industrial application of the results, it might have been better to have cooled the bars slowly as a preliminary treatment rather than to air cool them. It was now an accepted fact that although the transformations on cooling took place fairly quickly, it still required quite slow cooling for them to be completed and more especially with 1 per cent. tungsten and 0.2 per cent. chromium present. That was mentioned in connection with changes in length after the heat treatment, prior to hardening.

None of the heat treatments could be considered as an annealing of the normalised bars, for in each case the cooling (water or sand) was

too rapid. Because of those divergences from tool steel practice he thought it would be difficult for Mr. Brayshaw to stipulate what practicable annealing treatment he would prefer for bars of the steel used.

It was exceedingly difficult to discuss the changes in length after the different treatments, for to determine the nature of the latter would have required an extensive series of dilatation temperature curves. From the known behaviour of carbon steels the changes could be predicted qualitatively, but it was found that existing data did not explain the changes recorded. Since all the treatments of Table I., namely, heating to temperatures below the carbide solution temperature ($740^{\circ}\text{C}.$), caused contractions, it was evident that the normalising treatment had left appreciable amounts of carbide in solution. It was quite possible, however, that part of the change in length was due to the balling up of the sorbite. Whatever the cause it was not simple, for with increasing time at $739^{\circ}\text{C}.$ the decrease became less, and then after one hour increased again continuously. It was remarkable that not until the normalising temperature had been passed was there any increase in length or quenching from 732° and $725^{\circ}\text{C}.$, although many of the bars were glass hard, so that the $\gamma \rightarrow \alpha$ change, along with its expansion, had taken place, and the net expansion due to carbon in solution should have persisted. It was impossible to say whether that was due to the special elements present or was purely a function of the heat treatment.

Were the changes in length after the standard hardening referred to total change from the original normalised bar or to change after the preliminary treatment. In either case it was very difficult to explain the changes shown, for instance in Fig. 18.

Professor C. BENEDICKS (Stockholm) wrote that it was obvious, even at a hasty glance, that the paper was the result of important researches of great practical value, which, on account of the admirable minuteness and accuracy of details, might be supposed to be of a considerable interest for the theory of hardening. It was scarcely enough, however, to read and re-read the paper—it was necessary to work it through, with considerable energy, if its scientific bearing were to be made clear. In order to understand the physical conditions influencing the appearance of cracks at the test chosen by the author, it was necessary first to analyse the design of the test-cutter. In Fig. C it was easy to realise from *a* that hardening crack difficulties would be essentially the same if the teeth were formed symmetrically, as in *b*, or as in *c*. The quenching condition of such a cutter would be identical with the quenching condition of a prism of the form of *d*, provided that on quenching no heat were taken away from the prism through the lateral faces A and A' (which, being inside the cutter, were not exposed to the cooling liquid). Thus if A and A' were provided with an adiabatic coating, the quenching conditions of the prism would be equivalent to that of the cutter. Finally, instead of the adiabatic

coating, the surfaces B and B' might extend beyond A and A' (*d*), thus obtaining a truncated, symmetrical prism (lateral angles, say 80°), as indicated in *e*, with basis ABFGG'F'B'A'.

Such a test prism—very much simpler to make than the test-cutter—would give very nearly the same quenching result as the test-cutter, and had, in addition, the advantage of permitting an easy forecast of where the quenching cracks would appear. If the completed prism had the basal surface ACC'A' (*e*) instead of ABFGG'F'B'A', it was easy to see that, on quenching, it would be liable to crack, in the way roughly indicated by the curves *a* and *c*. As a matter of fact, if it were quenched from a high temperature, the metal, adjacent to the edge DE, and to the edges AD, A'D, and CE, C'E, would be cooled more rapidly and the outside of the prism would consequently be fixed or made rigid much earlier than the residual mass. When the cooling had proceeded

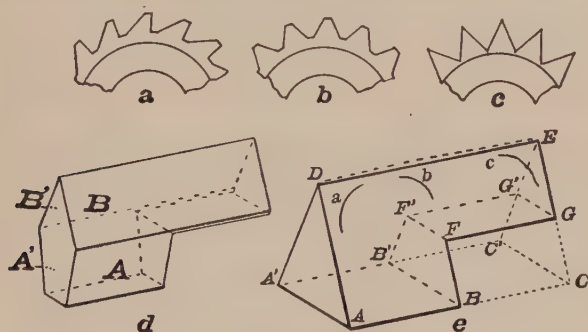


FIG. C.

to the interior of the prism, that interior portion would contract, thereby causing stresses, which would tend to extend to the outer parts so as to scale off from the (rounded off) inner portion. The main cracks resulting would be as *a* and *c*. Now, as the prism had not the basis ACC'A', but the basis ABFGG'F'B'A', the tendency to crack at *a* would be somewhat reduced, and that of cracking at *c* considerably lessened. Further, the final contraction of the bulk of the prism based on ABB'A' would cause the appearance of a crack at *b*. Now, all the cracks to be seen on Mr. Brayshaw's photographs (see, in particular, his Fig. 2, Plate VI.) were sufficiently well located as *a b c*, giving support to the above analysis.

The other form of crack, to be seen in the upper central cutter of Fig. 2, viz., two cracks parallel to the generatrix of the cylinder, was also easily explained. If the cooling, as would most frequently be the case, were much more energetic near the edge DE than near the basis plan ABFGG'F'B'A' (diagram *e*, Fig. C), the originally straight line DE, at nearer inspection, would be found to be slightly concave against the

basis—as indicated by the dotted curve DE (compare the well-known deformations of steel castings). If, on the other hand, the cooling at the surface FGG'F' by chance happened to increase in intensity, the edge DE would be slightly curved in the opposite direction. That would result in a stress, directed so as to separate the teeth from each other at the recess of the cutter. Thus, the appearance of cracks parallel with the axis is explained by admitting that, for some reason, the cooling was more effective than normally in the recess.

It was obvious that the relative intensity of the cracks would depend on the dimensions of the truncated prism; thus if the basis GG' was strongly diminished, no crack would appear at *c* but a very marked one would occur at *b* instead.

It had been questioned (by Mr. H. Brearley) whether the conditioning of the machined surface of the cutters had not perhaps more influence than the actual dimensions.¹ From the analysis given above it was evident, however, that that could not be the case. The conditioning of the machined surface could only cause slight dislocations of the situations of the cracks *a*, *b*, *c*—as was proved by the fact, that they generally occurred somewhat regularly in the quenched test-cutters.

Assuming a strictly definite configuration of the test prism, and a cooling action as regular as possible, the factors which would influence the appearance of cracks had next to be considered.

For given cooling conditions (quenching temperature; temperature of the cooling liquid) the liability to cracking would depend first on (1) the dilatation coefficient (admittedly a constant of the specimen). For silica, with a coefficient nearly = 0, no cooling cracks could be obtained. About the dilatation coefficient *per se* of hardened steel little was known, or had been published, but it seemed to be but slightly variable.

It would then depend on what could be designated as (2) the “brittleness” of the specimen. In copper, with a high dilatation coefficient, no cracking occurred, brittleness being absent. Now, the brittleness of quenched carbon steel depended firstly on the proportion of hardening carbon, or, as it was also called, dissolved or martensite carbon: the higher the hardening carbon content in a quenched steel specimen, the higher its brittleness. It would be quite conceivable, however, that with increasing hardening carbon the “ultimate strength” of the steel increased more than the brittleness. A given stress, then, would be less active in causing cracks; the higher the ultimate strength the less the liability to crack. It was possible, however, to leave that question out of consideration, as an increased content of hardening carbon was sure to increase the liability for cracking. As a matter of fact, with a high proportion of hardening carbon the effective dilatation, or better, contraction coefficient would

¹ *Engineering*, May 13, 1921.

be a high one. It was well known that martensite carbon occupied a much larger volume than the corresponding pearlite carbon; ¹ thus the effective contraction on cooling of the inner mass of a quenched specimen was increased by the fact that the content of hardening carbon was always somewhat less than in the outer parts.

In addition to the effect of the content of hardening carbon, the brittleness would be affected by the grain size, eventual heterogeneities of the cementite distribution, &c. In the present case, however, those probably were generally of minor importance.

Evidently, the liability for cracking was largely dependent on the quenching temperature and velocity, but as Mr. Brayshaw expressly had kept those factors constant, in the standard hardening from 760°, they did not need to be taken into consideration.

It was possible that the quenching velocity would, notwithstanding the standard hardening treatment, be slightly variable on account of some alteration of the surface of the cutters on prolonged soaking in the salt bath. He (Dr. Benedicks) thought that source of error could be entirely neglected. To sum up the foregoing argument, the most powerful influence on the appearance of hardening cracks in a carbon steel specimen would, with constant cooling conditions, be exerted by the proportion of hardening carbon. The higher that content, the more glass-like was the carbon steel (as to brittleness).

In Table VII., p. 152, the first extended series was that with a varying soaking time at 739°, B5 to B12. The specimens were first heated one hour at 825° and air cooled ("normalised"), then heated to 739° for varying time t , and then cooled in water ("water-quenched bars") or in sand. The Brinell numbers first given ("After Heat Treatment") referred to hardness then found. From the figures for B5 to B12, with $t = \frac{1}{8}$ to $t = 12$ hours, it was seen that the (Brinell) hardness after quenching in water increased with t from 241 to 600. Hence the conclusion, that the temperature used, 739°, was beyond the critical temperature (Ac1.2.3), which, as a matter of fact, was given as 738°. Thus, a specimen (B12) soaked twelve hours at 739° would after quenching contain more hardening carbon than, say, the specimen (B8) soaked one hour.

From B13 to B15, however, it was seen that, after the slow cooling in sand, the Brinell hardness was the same (228), and (from Table VIII. p. 166) that the corresponding cutters (C13, C14, C15) had nearly the same defectiveness (60, 57, 65).

The next extended series (soaking temperature 732, B16 to B25) was somewhat irregular (see Appendix VII.). The following series, with a soaking temperature of 725°, B26 to B35, was, on the other hand, very instructive. From the figures given for B26 to B30, the Brinell numbers were found after cooling in water continually to decrease with increasing soaking time t (241, 217, 207, 207, 201). In the same

¹ See, for instance, the determinations made by Dr. Benedicks in the *Journal of the Iron and Steel Institute*, 1908, No. II. p. 221, and Fig. 19, p. 223

way, the Brinell numbers found after cooling in sand regularly decreased with increasing t (223, 207, 197). It was to be concluded that the soaking temperature used here, 725° , was situated decidedly below the critical temperature (Ac1.2.3), and that a specimen with, say, $t = 12$ hours, must contain less hardening carbon than a specimen with, say, $t = 1$ hour.¹

Now, if the corresponding cutters, Nos. C31 to C35 in Table VIII., p. 166, or Fig. 12, Plate IX., were taken, it was found that simultaneously with that lessening of the hardening carbon in the cutter blanks occurred a very considerable amelioration of the quality of the cutters, the defectiveness numbers being successively 81, 71, 6, 6, 13. In the same way, for the specimens B36 to B43, soaked at 718° , a considerable decrease of the Brinell number was observed with increasing t , both for the water-cooled and the sand-cooled bars; and side by side with that softening of the steel used, a very considerable decrease in the defectiveness number occurred (C42, C43 giving 15, and 4 only).

That fact seemed to be a general one. Thus in the following table he (Dr. Benedicks) had collected the ten best cutters, and added the corresponding Brinell hardness numbers for the steel from which the cutters were made:

No.	Defectiveness No.	Brinell-Hardness of Sand-cooled Bars.	Blanks.	Med.
C155	1	170	187	179
C82	3	170	196	183
C43	4	197	197	197
C24a	4	207	207	207
C97	5	183	187	185
C232	5	207	196	201
C246	5	197	201	199
C135	6	187	187	187
C34	6	...	201	201
C33	6	...	207	207

On considering the mean values (strictly speaking the figures for bars and blanks should coincide, as in many cases they did), it was evident that a correlation existed between defectiveness and hardness numbers. Thus the two best cutters (defectiveness 1, 3) were made from the very softest material (hardness 179, 183).

¹ Of course, the softening of the metal on prolonged soaking might partly be due to an increased grain size; an increased grain size, however, could not account for the diminished liability for cracking. Likewise, it was possible that on prolonged soaking the cementite balled up to large globules, which were dissolved only slowly at the "standard hardening"; that, however, did not alter the above conclusions. The disappearing of stresses, which might result from the soaking at low temperature, likewise could have no sensible influence, as the subsequent quenching itself produced much stronger stresses.

How did that softness of the blanks act in lessening the liability to crack? The subsequent "standard hardening" (fifteen minutes at 760°) was a comparatively short period. If the steel before the standard hardening were especially soft, that probably depended on the fact that a considerable quantity of cementite, as globules, was precipitated in the metal—probably in a very regular way. Now it appeared to be quite plausible (especially if the retarding influence of tungsten, even in so small a quantity as 0.8 per cent.) were taken into account, that fifteen minutes at 760° were insufficient to dissolve the cementite entirely (or to a degree corresponding to saturation). At the end of the fifteen minutes, the proportion of dissolved carbon would be higher, if already, in the blank, the proportion of dissolved carbon was comparatively high. If, on the other hand, the proportion of dissolved carbon in the blank—owing to prolonged soaking at a temperature below Acl.2.3—were low, a comparatively low proportion of hardening carbon might be expected after the fifteen minutes of the standard hardening.

It resulted from those considerations that the cutters which had a slight liability to crack were those in which the content of hardening carbon at the final quenching was comparatively low.

It was very probable that if, for instance, the electrical resistance—which was a linear function of the content of hardening carbon—was determined for the hardened cutters, it would be found that the cutters with a low defectiveness number also had a low resistance value, though their hardness might be a sufficiently high one.

In concluding, Dr. Benedicks pointed out that from the earlier investigations of the author¹ we learned that an excellent method for hardening was the following: heat at a comparatively high temperature so as to destroy the crystallisation nuclei causing the splitting up of the martensite, cool down to just above Acl.2.3, and quench. The result would be: a comparatively high proportion of hardening carbon, persisting in spite of a comparatively slow, and consequently undangerous, quenching.

The present investigations also showed, according to Dr. Benedicks' opinion, that another excellent method of hardening might be this: soak the specimen at a temperature below A1.2.3, causing a considerable quantity of cementite to fall out, heat for a short period, say fifteen minutes, at 760° , so that only a part of the cementite goes into solution, and quench. The result would be: a quicker, and thus in itself more dangerous quenching, which however would cause no cracking on account of the reduced proportion of hardening carbon.

Both methods might have their advantages; it appeared to Dr. Benedicks that the new one might possibly be a considerable improvement.

¹ S. N. Brayshaw, *Proceedings of the Institution of Mechanical Engineers*, April and May, 1910, p. 517; compare p. 700.

Dr. McCANCE (Glasgow) wrote that in carrying out an extensive series of investigations involving a great many experiments and a large number of separate measurements, the labour involved could only be appreciated by those who had done similar work, and in reading that paper one appreciated the sacrifice of time and money which its preparation had entailed on Mr. Brayshaw. It was greatly to his credit that he had published the results, which must prove of value to many who used a similar steel for the purpose of making milling cutters.

The steel which he had chosen was naturally rather a difficult one to work and harden, but even so, it was surprising that none of the numerous cutters which had been made were entirely free from cracks. Knowing the accuracy of Mr. Brayshaw's pyrometrical work there was no question of inaccuracy involved, and one must look for other causes. The fact that after long annealing the tendency to crack was not removed—though it was diminished—seemed to point to the original steel bars having been badly treated before they came into his possession. The manufacture of such a steel was difficult, and small variations in the method of manufacture often led, from unexplained reasons, to a condition favouring cracking during hardening no matter what the prehardening treatment had been. From the large number of plain bars which also cracked during hardening, he was disposed to believe that such an influence had interfered to a large extent with the results.

Another disposing cause was the low temperature of the quenching water, which was maintained during all the experiments between the limits of 8° and 148° C. Now, cracking in tool steels nearly always took place when the material was below about 120° C., and that was towards the very end of the quenching operation. He (Dr. McCance) had often found that in difficult cases of hardening the tendency to crack was lessened, if not completely eliminated, by using a salt solution as a quenching bath and keeping the temperature between 20° and 30° C. The composition of the solution was immaterial so long as it was fairly strong, and there was no diminution in the degree of hardness obtained. It enabled the final cooling to take place at a slower rate towards the end of the process and consequently led to a more even temperature distribution in the bar and the volume change which occurred at the moment when the bar became magnetic did not occasion such severe stressing. That had been his own experience, and he would be glad to know if Mr. Brayshaw's had been the same.

If those two suggestions did not contain the explanation, then he was at a loss to know why cutters annealed at 732 and 706 should crack more severely than those which had been annealed at 718. There did not seem to be any theoretical reason why that should happen, and he thought that our present knowledge of the internal changes which took place in a steel bar was too well established to be upset in essentials.

Regarding the changes in length which had been recorded, he thought that the presence of a hole at one end of each test-bar had made the measurements unreliable, and that the large variations had been produced through the effect of that hole. It should not be forgotten as well that the change in length was as much a function of the shape of the bar as the condition of the steel, and the determination of the density was the only means by which the volume changes could be measured accurately. The correlation of the alterations in length with the shape had not so far been attacked systematically, and there was a large field open for a comprehensive research on the subject. The importance of the matter was unquestionable, and it was to be hoped that Mr. Brayshaw might deem it of sufficient interest to extend his work in that direction.

Mr. BRAYSHAW, in reply to the discussion, wrote that the time which elapsed between the issue of the advance copies and the meeting was too short to allow his paper to be properly studied, and so the most important part of the discussion was naturally to be found in the written contributions which came in later, but he wished heartily to thank those who had been willing to speak, even though they could only have a slight knowledge of what the paper contained.

Dr. Hatfield handsomely acknowledged the difficulty of explaining the results set forth, which was a satisfaction to him, as confirming the wisdom of his decision not to attempt a theoretical discussion at this stage. The data obtained were the outcome of a new line of research raising questions and suggesting possibilities which had not been discussed before. He was confident of his results, and if they stood, the bare fact remained that this tool steel could be so treated as to render it, for practical purposes, proof against hardening cracks, even under a ridiculously severe hardening treatment. He was pleased also that Dr. Hatfield had recognised the importance of further consideration of the Brinell-Shore ratio.

He referred to Professor Arnold's comments on the title, and drew attention to the fact that when he introduced his paper he stated that in the original MS. he had always used the expression a "low-tungsten tool steel," but he had since decided simply to call it a "tool steel." He trusted no one had been misled by the expression "tungsten tool steel" which appeared in the advance copies. If the statement were correct that the metallurgical effect of the tungsten might almost be neglected, it tended to corroborate his remark on p. 203 that "there is no reason to doubt that various steels covering a wide range would respond in a similar way." In any case, there was reason to believe that a plain carbon steel would have given remarkable results similar to those shown in the paper.

He was interested in the humorous remarks of Mr. Brearley about the commercial as distinct from the physical value of a small percentage of tungsten. He (Mr. Brayshaw) held that 0.8 per cent. of

tungsten had an appreciable physical effect, but not in the direction of reducing the liability to hardening cracks. Mr. Brearley hoped from the title of the paper that some brief rule would be given "which an observant hardener could follow in shop practice in order to produce tools with the great probability that they would not crack." Perusal of the paper would show that a more fundamental investigation had been attempted and more useful results achieved. He had submitted a mass of evidence showing how this steel might be so treated that difficult tools made from it could be hardened by the crudest methods with little or no risk of hardening cracks. That fact would have been recognised if he had only published a small fraction of his work, selecting the good results and showing how they were obtained. He considered, however, that the negative results were almost of equal importance. He had gone by steps from ordinary treatments to extremes, and by the fact of exploring the whole ground and obtaining bad results as well as good ones, he had been able to show something of the limitations as well as the possibilities of heat treatment prior to hardening.

He was able to state in response to Mr. Brearley's remarks about the condition of the machined surfaces that the special danger alluded to had been provided for. The fact was that the milling cutter was sharpened after milling a certain number of test cutters (see p. 208), the change being made before the cutter was dull. It would not have been necessary in commercial work to sharpen the cutter so often. It still remained true, as stated on p. 142, that discrepancies must have arisen in the machining, but the results on hardening showed how trifling such influences were in comparison with the potent factor of the previous heat treatment.

He thanked Mr. Brearley for his remarks about the steel, and he recognised the importance of his suggestions for pure metallurgical investigation, but from the point of view of this particular work there was a positive advantage in accepting the ordinary commercial steel with all its necessary imperfections. The author had had experience of great variations amongst bars made from the same ingot, and even between different parts of the same bar, but he had been surprised to find how trivial was the effect of such variations in comparison with what could be accomplished by heat treatment. Notwithstanding inevitable discrepancies arising from the lack of uniformity in the steel, and even in the face of possible original sin, as Professor Arnold called it, the fact emerged that nearly all the cutters had approximated in their behaviour to what the author predicted for them, and they were consistent with the bars. If great pains had been taken to secure uniform material it would have been objected, and reasonably so, that such an approach to a satisfactory sequence in such an elusive property as the liability to crack in hardening could never have been obtained from commercial Sheffield steel; and the metallurgical gain would have been purchased at the cost of throwing a doubt upon the

possibility of any practical value attaching to the conclusions. He would go further and say he would have had no difficulty in getting consistent results if the steel had been supplied by the same makers from a dozen different ingots made in the ordinary course of manufacture. It would be seen, therefore, that whilst he tried to carry out his own processes with precision, the practical value of the work was enhanced by the fact that the results set forth had been obtained with commercial steel. The steel for the research was made by Messrs. Kayser, Ellison & Co., Ltd., and they had supplied the following particulars as to its manufacture: "The bars were made from an 8-inch square ingot. This was rough-cogged under the hammer to 5 inches square, and after further heating re-cogged to 3 inches square. The $2\frac{1}{8}$ -inch round bars were then rolled from the 3-inch square. The flat sizes were taken from the 3-inch square billets, which were reheated and then cogged down to $1\frac{3}{4}$ inch square, afterwards finished to size under the tilt hammer." Questions about the eutectoid composition of a steel containing 1 per cent. of tungsten and so forth were ones about which he thought he might fairly look to Mr. Brearley for guidance. He referred to the solution of the carbide in his reply to Dr. McWilliam; and to his hardening in the salt bath in replying to Mr. Henshaw.

Dr. Hartley was right in supposing that Fig. 29 (p. 213) was representative of the records of temperature control. It had not been selected to show the furnace possibilities. There was no thermostatic control. An ordinary pressure governor was used for the gas. Variations in calorific value were sometimes troublesome, but were successfully dealt with by various artifices acquired by practice. Appreciable decarburisation occurred with some of the prolonged heats, but he assumed that that would not affect the hardness tests after the removal of $\frac{1}{64}$ inch, as described on p. 151. Dr. Hartley had raised an interesting point about the wetting of the surface of the metal by molten salts at high temperatures, but no trouble of that kind arose at the maximum temperature employed in that research. The author had clearly formed views as to the effect of the rate of heating and had a quantity of data about it; but it was a big subject, which he would not deal with at that time, except to say that the results would not have differed greatly from those shown if the pieces had been heated gradually instead of being immersed in the salt bath from the cold.

In answer to the question about a satisfactory hardening treatment, he believed he was the first scientifically to exploit the two-stage process for hardening. He had devoted prolonged study to hardening possibilities and had a mass of unpublished experimental data greater than what had been shown in the paper, but he did not propose to go into the matter now, as the immediate subject related only to preliminary treatment. Dr. Hartley had asked some interesting questions about the furnaces and pots, but he would ask to be excused from replying in that place on account of the length of the discussion, and he

also wished to concentrate upon the outcome of the research rather than upon the means employed.

He would point out with reference to Mr. Whipple's remarks, that the suggested standard hardening test was for the purpose of ascertaining whether the steel in question was liable to crack in hardening or not. Such a test would generally be considered impracticable because of the erratic and unaccountable results in connection with hardening which were so common that they were accepted as inevitable. He believed that the behaviour of steel could be brought completely under control, provided it were reasonably sound and not objectionable in analysis. The proposal would not appear far-fetched when the facts set forth in the paper were fully appreciated.

Mr. Brayshaw valued Professor Turner's remarks with regard to volume changes, and he certainly felt that information of great value might have been obtained if the specific gravity had been taken in all cases. The measurement of lengths was not supposed to indicate volume change. The research had a direct and immediate application in the hardening of gauges and tools in which the change in length was of vital importance. Information was given in the paper which would enable such tools as taps and screw gauges to be hardened with little or no change in length, or if the necessary treatment were given they could be depended upon to lengthen or shorten by a given amount as desired.

Mr. Hothersall had drawn attention to the question of surface decarburisation, and had produced interesting experimental data which might be important, but could hardly be interpreted without further information. In any case he agreed that the possible effect of partial decarburisation should not be forgotten.

In reply to the correspondence, Mr. Brayshaw wrote that he was pleased that Dr. McWilliam had looked at the paper as a whole and had focused attention on the vital conclusion and practical utility of the research. He agreed that one would have expected the heating for hardening to neutralise the effect of the previous heat treatment, but the evidence put forward was, he thought, conclusive. He had not proved that all the cementite went into solution on heating for an hour at 825° C. He supposed that the carbon did not go into solution as cementite but the cementite dissociated progressively, and if he had considered the sentence he would have preferred to speak of the carbon going into solution without stating the temperature at which the process would be complete. For the purpose of the research, however, he attached no importance to the question of whether all the carbon went into solution or not at the temperature fixed upon. The point was that the bars and blanks were first heated alike to 825° C. for an hour, and the so-called normalising must be regarded as bringing all the pieces into the same condition so far as possible rather than as aiming at the complete solution of the carbon.

Professor Rejtó in his interesting remarks spoke of the sulphur

and phosphorus contents as being high. They were not high, however, for English steel even of the best class. No doubt the percentage was high in comparison with Hungarian steel made from Styrian iron, but he did not believe that the presence of these two elements had perceptibly affected the hardening results. He had no doubt about the correctness of the observation that of the test-bars which were quenched from the heat treatment (measured after such quenching and before the standard hardening) those which were heat treated with a maximum temperature of 750° or 800° C. shortened with the quenching. In that connection it was important to keep in mind the distinction, brought out by Professor Turner's remarks, between change in length and change in volume. Professor Rejtö made an interesting attempt to explain the high Brinell-Shore ratio of the most cracked cutters by suggesting that "in the case of minute cracks the Brinell number remained a maximum whilst the Shore number decreased because the cracks impaired the elastic properties." Although he could not accept that explanation, the matter might well be considered further along those lines. He did not suggest that any hardness was conferred at 706° C. His reference to that temperature on p. 182 was quite incidental, the point being that Fig. 15 (p. 184) was remarkably consistent except for one observation, which happened to be for a bar treated at 706° C.

He wished to thank Professor Carpenter for his contribution, and particularly because he had referred to the practical outcome of the work done. No full explanation of the results was yet forthcoming, but further research on the Ac and Ar transformations, as suggested by Dr. Carpenter, might throw light on the subject.

He was pleased to read Sir Robert Hadfield's remarks. The paper which he (Mr. Brayshaw) gave to the Institution of Mechanical Engineers in 1910 recorded a great amount of research which largely consisted of feeling the way towards the work he had now published. It was good to know that that paper had been useful, and still more, that he had now got on to the track he was then in search of. The encouragement and assistance of Sir Robert Hadfield had been a great help to him.

He welcomed Mr. Henshaw's valuable communication and only wished Mr. Henshaw had given particulars of the treatment referred to in his opening paragraph by which he had arrived at the same freedom from hardening defects, because such publication could not fail to be an event of the greatest importance to tool-makers everywhere. The method of hardening adopted in the research was criticised on the ground that the defects would not be produced by the heat treatment the steel had received, but by the hardening. Let that be granted, and powerful emphasis was laid on the astonishing effect of a heat treatment which prevented the cracks even under those conditions. The object was to test the effect of the heat treatment with the utmost severity, and therefore the blanks were machined into cutters of an extreme design, which cutters were drastically

hardened by severe heating and risky quenching. When after introducing every element of risk certain treatments consistently succeeded, his conclusions were immeasurably reinforced. True, such drastic hardening necessarily involved the cracking of the great majority of the cutters, but only so could the full lesson be learnt. Good hardening would have saved many cutters, but would not have so clearly indicated the direction of progress. In that connection it was important to note the confirmatory testimony from the bars, which were not so liable to crack as the cutters. (See "Hardening Cracks in Test-Bars" on p. 150, and "The Cracking of Test-Bars" on p. 196, also Appendix VIII., which dealt with the cracking of test-bars in relation to the defectiveness of test-cutters.) He was pleased that his observations had been so far confirmed by Mr. Henshaw's differential curves; and the further halt at 682° C. was of great interest, particularly as he had received a letter from Professor Tammann of Göttingen suggesting the possibility of such a point. The micrographs confirmed the evidence from the curves. That was a clue which ought to be followed up, though he did not see yet how to fit it in with his own work.

He thanked Dr. Schwinning for his remarks, and would emphasise what he had said about very uniform distribution of the cementite. It might be that more depended than had been supposed upon even the ultra-microscopic distribution of the elements.

He would refer Mr. Greenwood, who wrote about the design of the test-cutters, to his reply to Mr. Henshaw, who criticised the hardening process. Close study of Tables IX. to XII. in connection with Appendix VIII. would show how consistent were the results in comparison with what might be expected when dealing with such an intangible subject as the liability to crack in hardening. It was only for the normalising or preliminary treatment that the bars and blanks were air-cooled after heating to 825° C. for one hour, and the object was to bring them all for a start, into the same condition, and that condition was to be distinctly bad, so that any good results should be attributable solely to the heat treatment. He was quite prepared, however, to entertain Mr. Greenwood's suggestion that it would have been better to cool the bars slowly for that process, and he recognised that there would have been certain advantages in so doing. On the other hand, he certainly thought it was right for the heat treatments to be followed by water-quenching or sand-cooling, even though the latter process might not be regarded as an annealing. The sand-cooled bar B82 was even softer than the well-annealed bars B1 and B2, and it was difficult to suppose that it could have been much different if it had been cooled very slowly from 718° , especially in view of the fact that its companion bar B78, which was water-quenched, was also very soft. It was instructive to observe the slight difference in hardness after heat treatment between B78 and B82. These two bars had been taken as examples at random, but many other similar comparisons could be made. It remained true that in many instances a slow cooling

would have made a great difference, but in so far as that might be the case, was the quicker cooling justified, for the object was to ascertain what took place at certain temperatures, and it was evident that the effect would be partially obliterated by subsequent slow cooling. The procedure which was adopted located where the vital annealing took place. Bars B78 and B82 and cutter C82 showed what extraordinary results could be produced by a heat treatment without even going to the trouble of annealing in the accepted sense of the word as used by Mr. Greenwood. It certainly would have been interesting to have the results of another series in which the same heat treatment had been followed by very slow cooling, but he doubted if much additional information, except of a negative character, would have been gained thereby. On the other hand, the suggestion made on p. 201 for the water-quenching of a series of cutter blanks after heat treatment would have provided fresh food for thought.

In all cases the change in length was given as the change due to the process in question and not the total change from the original or the normalised bar, thus the change in length due to hardening represented the difference in length of the bar before and after hardening. With regard to Fig. 18 (p. 188), he must say that the changes shown were not abnormal, but were such as he was well acquainted with. Although no explanation was forthcoming, the importance of that figure and of Fig. 15, from a practical point of view, would be gathered from a moment's consideration. Figs. 18 and 15 must, of course, be studied in connection with Figs. 17 and 14.

He was glad to see Mr. Greenwood's concluding remark that the work should be followed up on the scientific side, so that the results contained in the paper might be explained on a rational basis. It was perhaps not surprising that there had been so little attempt to explain the behaviour of the steel. The results would, of course, be utilised, but there could be no satisfaction until they were discussed and understood.

Mr. Brayshaw wished heartily to thank Professor Benedicks for his communication. His comments upon the manner of cracking were valuable, though, as a matter of detail, Mr. Brayshaw could not agree that cutters made with symmetrical teeth, as in Fig. C (*b* or *c*), p. 233, would afford quite so severe a test as cutters with teeth, as shown in *a*. When very slight cracks appeared on the test-cutter they were usually on the radial face, and it was only as the cracks became more pronounced that they extended to the backs of the teeth. It was rare for a crack to appear on the back of a tooth and not on the face. Some of the cutters with a low defectiveness would have been perfect if made as *b* or *c*. The author was particularly pleased with the suggestion for a test prism, and the slight objection referred to above would be met if it were made as shown in Fig. D, which would be easy to make from a rectangular section. True, such a prism would fail in other ways to reproduce the conditions of the test-cutters, but it would on its own

account afford ample opportunities for cracks to develop and would constitute an excellent form for a standard test of liability to crack in hardening.

Dr. Benedicks' discussion of some of the results was illuminating, and his suggestion that the absence of cracking in certain cutters was caused by a reduced amount of dissolved carbon in the hardened pieces, might be the correct explanation. If so, it would appear that the carbon, presumably in the form of cementite, could be brought into such a condition, by balling up or otherwise, that its tendency to go into solution on heating was substantially lessened; and the best

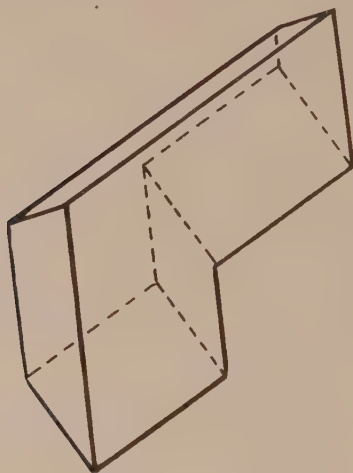


FIG. D.

method of producing that condition would become a matter of the first importance in any consideration of the hardening of tool steel.

The following were some of the considerations which must be taken into account in connection with Dr. Benedicks' theory. The ten best cutters had low hardness figures, but other cutters, which were equally soft as some of those, broke badly. Cutters C1 and C2 were very soft, but they cracked particularly badly. The balling up of cementite might proceed without greatly affecting the hardness, but such balling up might increase the resistance both to dissociation and to the solution of the carbon. The hardness of the hardened cutters was not ascertained, but there was no reason to doubt that it was fairly constant as shown by the bars; which was not what would have been expected if the difference in behaviour were caused by varying proportions of dissolved carbon. Dr. Benedicks supposed the cementite to have been precipitated as globules in a very regular way, and it might be that the regular distribution was an essential factor as well as the con-

dition which resisted the passage of the carbon into solution. The bars and cutters were all available for further tests, and the suggestion to determine the electrical resistance would not be lost sight of.

In thanking Dr. McCance for his remarks, Mr. Brayshaw said he thought further consideration would show that it was scarcely to be expected that any of the cutters would be absolutely free from cracks, and in that connection he would refer to his reply to Mr. Henshaw. Also, it must be remembered that special means were taken (see p. 164) to discover minute cracks. Many of the cutters would have been passed as perfect if they had been subjected only to an ordinary examination. The number of bars which cracked was quite in accord with Mr. Brayshaw's expectations considering the heat treatments and the severity of the hardening. Except for bar B208, there were no cracks except around the hole, which afforded a good start. He thought that the steel as received by him was as good as any such steel that could be obtained. From a large experience he could say confidently that there was no annealed steel obtainable in England that would not show bad breakages if made up into those test-cutters and given the standard hardening treatment described on p. 149.

Dr. McCance referred to unexplained reasons for cracking during hardening no matter what the previous treatment had been, and a speaker in the discussion made a statement that would commonly be accepted as a truism or a platitude when he said that anyone engaged with tool steel knew that with exactly the same treatment, carried out with the greatest care, it was often possible to get strangely discordant results from the same bar. The difficulties of tool steel hardening were so great, and so little understood, that even scientists seemed to give way to a kind of fatalism on the subject. He would oppose to that his own statement on p. 203, that "even in the case of the most difficult article, there is no mysterious fate to decree inexplicable breakages or failures." He was not prepared to acquiesce in an admission of impotence in the face of the strangely discordant results of which he might fairly claim to have exceptional experience both as to occurrence and prevention. He had dealt with the question of the steel in his reply to Mr. Brearley, but he would say here that no one could master the significance of Figs. 9, 12, 20, 22, 25, 27 and 28, and Tables IX. to XII., without realising that some, at least, of the unexplained behaviour was now within our control. All the cutters shown on those figures were hardened alike. Some of the cutters were badly broken, and some were fairly sound, and even of the sound ones, some were good and some were bad so far as their strength was concerned, and yet they were reasonably consistent throughout with scarcely half a dozen exceptions; furthermore, those results were in general accord with those obtained from the bars before and after hardening. The difference in behaviour was determined by the fact that the blanks from which the cutters were made had been treated at various temperatures for various periods of time. That was to say, the very same

hardening produced the strangely discordant results which were the despair of tool-steel users, but his research had laid bare the cause of the discrepancy so far as the actual treatment was concerned, and the relation between cause and effect was manifest for all to see whatever might be the explanation.

Dr. McCance had made some useful remarks about quenching, and undoubtedly the low temperature of the quenching water had added to the severity of the hardening which increased the significance of the fact that some of the cutters hardened satisfactorily.

It certainly was surprising that the cutters annealed by cooling to 732° should be hopelessly bad, whilst 718° produced satisfactory results; but there was a sufficient mass of evidence to show that it really was so. He (Mr. Brayshaw) agreed that the hole at one end of each test-bar had impaired the value of the length measurements as indeed he had stated on p. 196, but he doubted if the presence of the hole had accounted for large variations.

Reviewing the discussion as a whole, he felt that in dealing with tool steel there was too often a sort of tacit acknowledgment, not only that there was something unknown, but something unknowable. To not a few it was almost impious to suggest that industry urgently demanded more knowledge about such matters as the transformation changes or the distribution of carbon, and the time it took to go into solution, and yet a whole series of results had been shown which no one had challenged and scarcely anyone had ventured to explain.

The paper was written to draw attention to a certain desirable condition into which tool steel might be brought prior to hardening. The condition in question might well have escaped notice in the past, for apparently it could not be detected by analysis or by ordinary hardness tests, neither was it shown by the microscope at 500 diameters, and no indication of it appeared to be forthcoming from bending tests, yet it produced a change in behaviour which made all the difference between success and failure in hardening. It was of practical interest that a particular treatment previous to hardening brought the steel into a condition that had not hitherto been recognised but which was of the very first importance to the hardener, who knew only too well about unaccountable occurrences both as regarded cracking and changing in length. By an intelligent application of the information given not only would hardening losses cease, but there would, as explained on p. 203, be a great increase in efficiency. The theoretical explanation might be very simple, like the one offered by Professor Benedicks, but the fact would lose none of its importance thereby.

In the state of knowledge and practice which had obtained in the past, the suggestion of a standard hardening test (see p. 202) seemed merely fantastic, but it was put forward as a serious proposal. The author had shown that ordinary tool steel could be so treated that the tendency to crack in subsequent hardening was almost eliminated, and a simple test carried out with only a fraction of the knowledge and skill

required for making an analysis would show whether the steel was in that condition or not.

The paper contained such a mass of data and information, that it had been manifestly impossible to give adequate attention to it in the limited time allowed for discussion, but no doubt the correct theory would emerge, and in the meantime the results could be applied by the makers and users of steel.

Iron and Steel Institute.

ON THE CAUSE OF QUENCHING CRACKS.

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1. It is a well-known fact that during the quenching of high carbon steels in water, cracks are often formed on their surfaces. The cause¹ is generally believed to be :

- (i) The non-uniform distribution of temperature in the specimen during quenching.
- (ii) The difference in martensitic expansion of adjacent parts during quenching.

A closer examination of the phenomenon shows, however, that the true cause is not so evident, as the sound due to cracking is often heard some ten seconds after quenching. The thermal stress is maintained so long as the temperature is not uniform throughout the specimen. For instance, in a short cylinder, about 2 centimetres in thickness and height, the difference in temperatures between the interior and exterior parts, during the first stage of the quenching process, may amount to several hundred degrees, and consequently a great stress will result, but after about ten seconds it does not exceed 20°, and hence there is only a small residual stress. Again, at the moment of transformation of austenite into martensite during cooling, considerable expansion in volume occurs. In the case of rapid cooling the transformation does not, however, take place at the same moment at every point within the specimen. Hence a great stress due to unequal martensitic expansion will result which may lead to cracking, although after several seconds, during which the A1 transformation passes over the whole mass, this stress will also vanish.

If the cracks were due to the two causes above-mentioned, why do they not take place during the first stage of quenching, when the specimen is undergoing a large amount of internal stress, and why do they take place after a lapse of time? It

¹ McCance, *Journal of the Iron and Steel Institute*, 1914, No. II. pp. 235, 247.

From the above table it is seen that during heating the crack does not occur unless the quenching temperature exceeds 800° . During cooling from 900° the quenching crack is always observed down to a temperature of 700° , and not observed at any lower temperature. This limiting temperature is much lower than that during heating. As is well known, the Ar1 point is always lower by about 40° to 80° than the Ac1 point; hence, from the above result of quenching experiments, it may be concluded that during heating or cooling the crack occurs when, and only when, the quenching temperature exceeds the Ac1 or Ar1 point, respectively. Hence the cause of quenching cracks is not pure thermal stress caused by non-uniform distribution of temperature due to rapid cooling, because if such were the case, there would be no reason for the cracks occurring beyond the A1 point. The cracks must, therefore, have some connection with the A1 transformation.

In a soft quenching, cracks usually occurred in ten to fifteen seconds after quenching in water; they could be distinctly detected by the sounds accompanying cracking. The same fact also indicates that the thermal stress is not the direct cause of cracking because the cracking occurs after a lapse of time, where a greater part of the thermal stress due to the unequal cooling of the specimen passes off. As is well known, during cooling through the Ar1 point the specimen undergoes a considerable expansion due to the A1 transformation.¹ Since during cooling the outer portion is always at a much lower temperature than the inner portion, the former, during the said transformation, exerts a great impulsive tension on the latter, and this may cause a crack in the specimen. But the fact that cracks often occur after the impulsive stress due to the Ar1 transformation is passed over, shows that the impulsive stress is not the actual cause of quenching cracks.

It was also thought desirable to make a similar experiment with a specimen having no A1 transformation, which was, however, at least as brittle as quenched carbon steels. An alloy steel containing a considerable amount of chromium and cobalt possessed such a property. The experiment with the steel showed that, from 550° upwards, very superficial but irregular

¹ K. Honda, *Science Reports*, vol. vi. (1917), p. 203.

cracks gradually appear, but vanish, however, with a light polishing. As the quenching temperature rises, the cracks become deeper and deeper, but remain always irregular. Quenched from 1000° , they are still much finer than those in carbon steels. The quenching of a cast iron from different high temperatures shows also similar cracks. Thus, crack lines due to pure thermal stress are very fine and irregular, and can easily be distinguished from very simple crack lines (Fig. 1) in quenched carbon steels, which are the object of the present investigation.

3. To get a general idea of the rate of cooling during quenching, a cylindrical piece having the same dimensions was made of the same material as the test specimens. It had two holes bored parallel to its axis and to its middle height, their inner diameter



FIG. 1.

being each 2 millimetres ; one hole was bored at its centre and the other just inside the lateral surface. In one experiment a platinum and platinum-rhodium couple was well insulated and inserted into the middle hole, its junction being, however, bare and in direct contact with the specimen, while the other hole was packed with kaolin. In another experiment the couple was inserted into the side hole while the central hole was packed with kaolin. In each case the cooling was measured by a millivoltmeter with a pivoted needle inserted in the circuit of the couple, the motion of the needle being almost dead beat. Fig. 2 shows graphically the result of the observations. From curves (1) and (2) it is seen that the temperature of the specimen at its centre and at its lateral surface falls initially very slowly, and then rapidly, increasing in its rate till it reaches a maximum and then gradually decreases. Curve (3) is the difference-curve between curves (1) and (2) ; thus the difference in temperatures between the centre and the lateral surface is at first zero, but rapidly increases, reaching its maximum value at about 3.5

seconds and then decreases, till it almost vanishes at 13 seconds. The maximum difference in temperatures in the specimen amounts only to about 300° .

4. The result of quenching experiments will be next described. The investigation consisted of the measurement of hardness in quenched specimens by means of a Shore scleroscope, the distribution of internal stress being thus found. Four kinds of

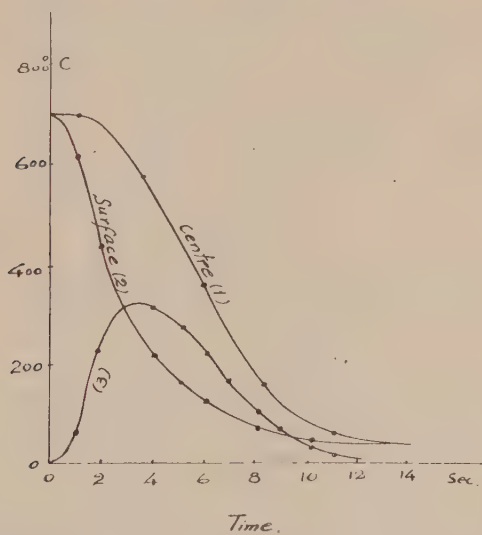


FIG. 2.

carbon steel containing the following constituents were chiefly investigated :

No.	Carbon per Cent.	Manganese per Cent.	Silicon per Cent.	Phosphorus per Cent.	Sulphur per Cent.
1	0.28	0.25	0.42	0.032	0.070
2	0.68	0.51	0.19	0.019	0.037
3	0.91	0.31	0.11	0.027	0.004
4	1.47	0.25	0.34	0.040	0.004

The specimens were tested in the form of a cube, each side being 2.7 centimetres, or a short cylinder, 2.6 centimetres in

diameter and in height. On a surface of the cube or the cylinder a narrow hole, about 3 millimetres deep, was bored, and a thick steel wire screwed in, as shown in Fig. 3; this wire served as a holder in the subsequent work. The specimen was placed horizontally in an electric furnace of nichrome wire, and heated to the required temperature. After maintaining the specimen at this temperature for ten minutes, it was quickly taken out of the furnace and dipped vertically into a water or oil bath, followed by a constant stirring, until the temperature of the

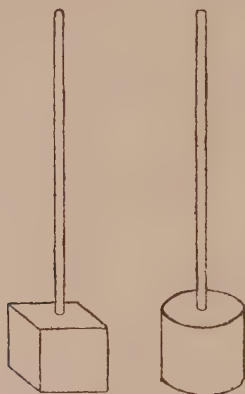


FIG. 3.

specimen fell to that of the bath. The specimen thus quenched was polished with emery paper; sometimes it was at first ground with carborundum, care being taken, by dipping it frequently in water, not to heat the specimen too much, since heating may affect the structure and consequently its hardness. The specimen was placed on the platform of a Shore scleroscope, and the position of a point, at which the hardness was to be measured, was read on a section paper pasted on the platform. In the case of the cubes, the number of points by which the hardness was measured amounted to 36, and sometimes more, if necessary. These 36 points were divided into three groups, the outer group consisting of 20 points at the periphery, the inner group 4 points about the centre, and the middle group 12 points situated between these two. In the case of cylindrical specimens, the number of points amounted to 24 in all, the outer group being 12, the middle 8,

and the centre 4. In cases when the general character of the distribution of hardness is to be sought, the mean value of hardness in each group was taken.

The results of experiments showed that :

(1) In a soft quenching, such as in oil from a temperature not exceeding 820°C ., the hardness of different specimens is greatest in the outer portion, and decreases from its periphery towards the centre.

(2) In a medium quenching, such as that of a steel 0.9 per cent. carbon at 780° in water, or that of steel 1.47 per cent. carbon at 900° in oil, hardness is nearly constant everywhere.

(3) In a hard quenching, such as that of steel containing more than 0.68 per cent. carbon from 800°C . or a higher temperature in water, the hardness is least in the outer portion and increases rapidly toward the centre.

(4) When cracking takes place, lines of cracking cut equi-hardness curves almost orthogonally. The form of equi-hardness curves is elongated in a direction normal to the line of cracking.

(5) In the cubes, the equi-hardness lines become roughly circular or elliptical at a short distance from the periphery. The same remark applies naturally to the case of cylindrical specimens.

(6) By grinding away a few millimetres from the surface layer step by step, the irregular deviation of equi-hardness curves from a circle or an ellipse gradually diminishes.

In the present experiment, cracking occurred in most cases, when the temperature of the specimens fell nearly to that of the bath. To show the relation between the hardness and the quenching temperature, the results of experiments are given in Figs. 4, 5, from which the following well-known facts may be inferred :

(7) The hardness does not increase appreciably, so long as the quenching temperature is below the Ac1 point.

(8) When the quenching temperature increases beyond the beginning of the Ac1 range, the hardness rapidly increases, reaches a maximum at about 820° , and afterwards slightly decreases.

From the curves in Figs. 4, 5 we also see that the hardness of the outer portion is least, that of the middle portion considerably greater, and that of the central portion greatest.

5. One important fact discovered by the present investigation (3) is that in a hard quenching the outer portion is softer than the inner. This abnormal phenomenon is satisfactorily explained by the theory of quenching put forward by one of the present writers.¹

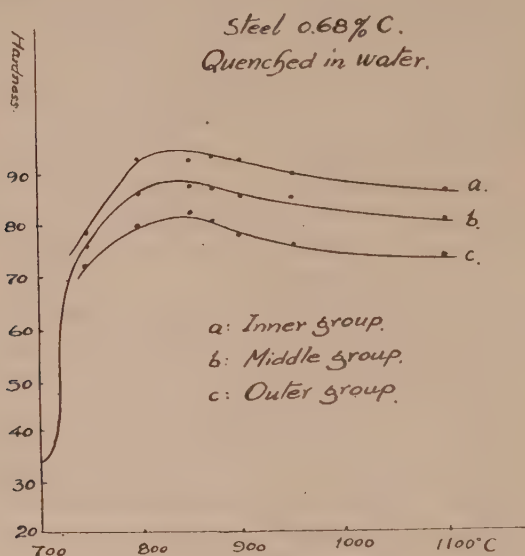


FIG. 4.

According to that theory of quenching, the so-called A1 transformation is not a single, but a compound transformation, consisting of



Thus, during a slow or rapid cooling, austenite is at first changed into martensite, which is then transformed into pearlite. During a very rapid cooling, such as a quenching, the change from austenite to martensite is so far retarded that when it is completed the specimen is nearly at room temperature, and therefore the next change from martensite to pearlite cannot progress, owing to the high viscosity of the material at room temperature.

¹ K. Honda, *Science Reports*, vol. viii. (1919), p. 181.

During a slow cooling austenite changes into martensite, and the latter, still at a very high temperature, changes immediately into pearlite. During heating, the A1 transformation consists in the reverse change, that is, from pearlite to austenite through martensite.

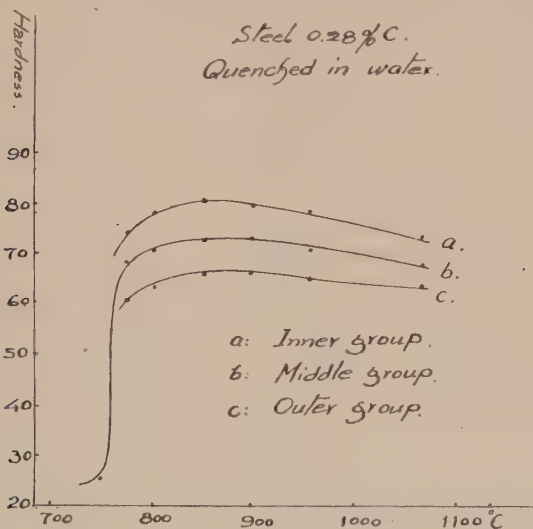


FIG. 5.

With regard to the volume per unit of mass, the relation is :

$$\text{Austenite} < \text{martensite} > \text{pearlite};$$

for martensite is known to exist in a more dilated state than pearlite, and the latter in a more dilated state than austenite, as is seen from the expansion curves¹ at high temperatures. Hence in the A1 range, during slow cooling, the elongation is a differential effect of the expansion due to austenite \rightarrow martensite and of the contraction due to martensite \rightarrow pearlite; during slow heating, the contraction is a differential effect of the expansion due to pearlite \rightarrow martensite and of the contraction due to martensite \rightarrow austenite.

In quenching experiments, the rates of cooling in the outer and inner portions of the specimen differ considerably from each

¹ K. Honda, *Science Reports*, vol. vi. (1917), p. 203.

other. In the outer portion, where cooling is very rapid, not only the second change of the A1 transformation—martensite to pearlite—is stopped, but also its first change—austenite to martensite—is partially arrested, so that this portion contains a certain amount of austenite intermingled with martensite. In the inner portion the rate of cooling is not so rapid, and hence the austenite is mostly transformed into martensite; but its further transformation into pearlite is arrested. Since the austenitic structure is much softer than the martensitic structure, it is to be expected that the outer portion, containing a greater proportion of austenite than the inner portion, will be softer than this portion.

If the above view be correct, for a soft quenching, such as quenching in oil from a moderately high temperature, the outer portion may be just fully martensitised, while in the inner portion the transformation from martensite to pearlite is partial. In this case, the outer portion must be harder than the inner portion, as is actually brought out by experiments. In a somewhat harder quenching than in the last case, the outer and inner portions may possess nearly the same hardness. The fact that above 820° the hardness gradually decreases as the quenching temperature increases, is explained by the same theory, that is, by a gradual increase of austenite arrested and mixed in martensite.

Several quenched specimens were examined microscopically to see whether any appreciable decarburisation actually occurred; but except narrow edges, or at least in portions where hardness was measured, decarburisation was negligibly small. Hence the less hardening of the outer portions cannot be explained by decarburisation. It is the common experience of smiths that by quenching pieces of steel in water, the edges are much softer than other portions; this fact is usually explained as the effect of decarburisation during heating. In many cases, however, it is caused by the arrested austenite during quenching.

The cause of cracking was next investigated in a series of equi-hardness curves for a number of carbon steels with varying percentages of carbon, quenched from varying temperatures. These curves accompanied the original manuscript, but as their reproduction would have been attended with certain difficulties,

they have been omitted from the paper, and are filed in the Institute library, where they can be consulted by any member interested in the subject. Since the form of the equi-hardness lines was elongated in the direction perpendicular to the line of cracking, it is to be concluded that the martensite development is greatest in the elongated central portion and least in the periphery; hence the martensitic expansion in the former portion is much greater than that in the latter portion. The central portion exerts, therefore, a great tension on both sides, this tension causing the cracking of the specimens. This is why lines of cracking are normal to the elongated equi-hardness curves. Since the difference in the specific volumes for martensitic and austenitic structures increases rapidly as the temperature falls, it may be understood why cracking generally occurs when the temperature of the specimen approaches to room temperature.

6. Having thus far explained the distribution of hardness and crack lines, the question of how to avoid quenching cracks arises. In quenching practice it is not necessary to get very great hardness, except in the case of cutlery. It is also evident from the above investigation that to obtain a martensitic structure too rapid cooling is unnecessary. In order, therefore, that the specimen may not crack during quenching, but that its hardness be properly developed, quenching must be medium hard, such as quenching in oil from 900° , in which case the hardness is nearly constant throughout the specimen; hence the stress due to the difference in the structures is small, and consequently cracking cannot occur. For a given steel, the quenching temperature of no cracking can be experimentally found in the following way: The specimen is quenched in oil from three different temperatures, 800° , 900° , 1000° , and the hardness at the outer and central portions is measured. Two curves of hardness-quenching temperature for these two portions are drawn. The temperature corresponding with the intersection of these curves is that required; for quenching at that temperature causes nearly equal hardness in the outside and central portions.

7. According to the above view, in a hard quenched steel some austenite remains untransformed at room temperature, at which this austenite will slowly transform into martensite. On the other hand, at room temperature martensite has a tendency

further to be transformed into troostite, but its velocity is much smaller than that of austenite \rightarrow martensite just referred to. The consequence is that at room temperature a hard quenched specimen will slowly increase its hardness with lapse of time. To test this inference the hardness of a quenched specimen was measured from time to time in the usual way, and its mean value plotted against the time passed after the quenching. Fig. 6

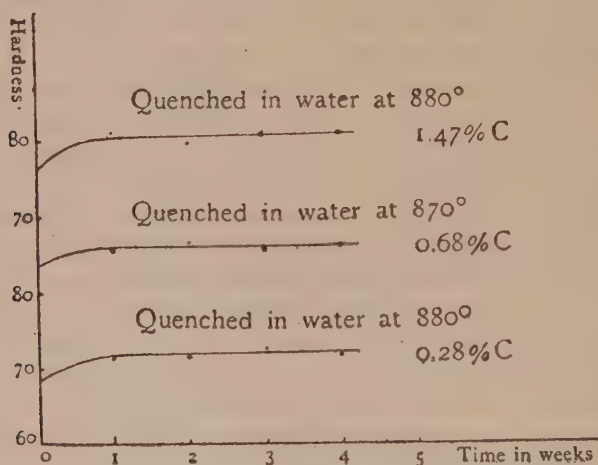


FIG. 6.

is a graphical representation of the result of the experiment, which agrees completely with expectation. The hardness increases at first rapidly and then slowly, tending to an asymptotic value, as the time elapses.

If the quenched specimen be constantly heated at 100° , instead of letting it remain at room temperature, the above change from austenite to martensite will be much accelerated; at the same time the change from martensite to troostite will also be accelerated. Hence the hardness first increases, reaches a maximum, and then slowly decreases. As shown in Fig. 7, this conclusion is actually brought out by experiments.

8. In quenching a large piece of steel the distribution of hardness in the outer layer is exactly the same as in the case so far discussed; but in the innermost portion, where cooling is

slow, the microstructure becomes troostitic, and therefore the hardness is here considerably smaller.

Now, the contraction-temperature curve for steel rod during slow cooling¹ or quenching² has been already determined and found

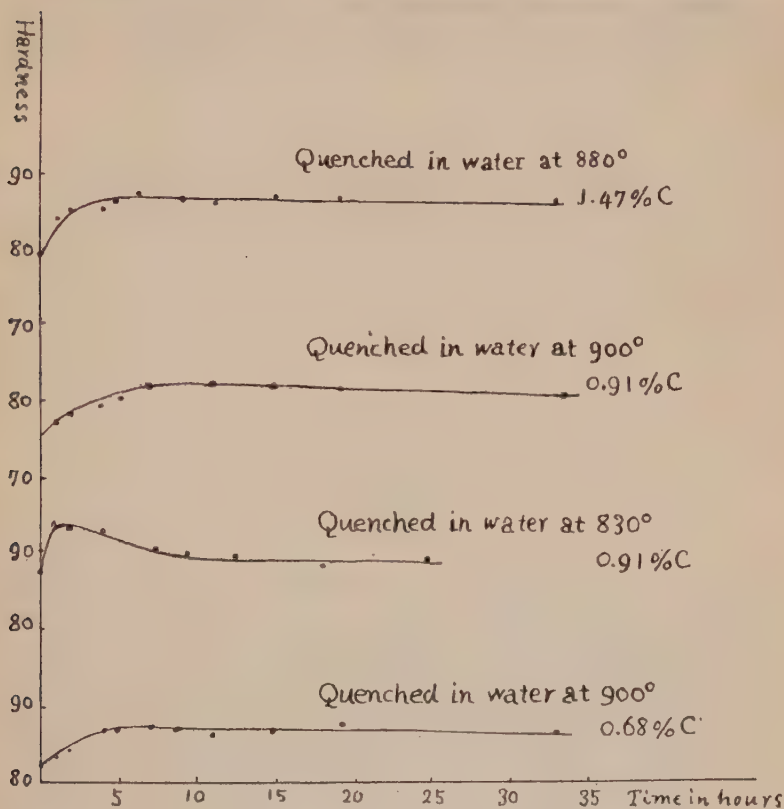


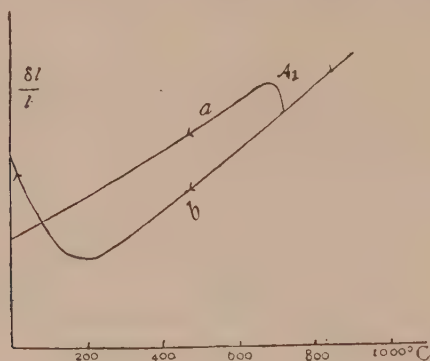
FIG 7.

to have a form as shown by curve (a) or curve (b) in Fig. 8. The curve (a) is the ordinary contraction-curve for a slow cooling; the curve (b) for quenching begins to elongate from 200° downward, and at ordinary temperature the length of the rod is much larger than that in the case of slow cooling. This elongation is

¹ K. Honda, *Science Reports*, vol. vi., loc. cit.

² *Ibid.*, vol. viii. (1919), p. 169. P. Chevenard, *Comptes Rendus* (1919), p. 17.

the expansion accompanying the transformation from austenite to martensite, the further transformation from martensite to pearlite being arrested. Hence, in quenching a large specimen, its outer portion contracts along a curve similar to curve (b), while the inner portion contracts in a manner similar to curve (a), and therefore during cooling through the A1 range the inner



a: slow cooling,
b: quenched.

FIG. 8.

portion is in a more dilated state than in the latter portion. Hence the outer portion undergoes a large tension, and this tension superposed on the thermal stress may cause the cracks in the specimen at high temperatures. In a hard quenching, crackings are often found to take place immediately after quenching in water; this kind of crack is probably due to the stress just referred to. By a further cooling of the specimen, the tension acting on the outer portion begins to decrease at some 200°, becoming zero at a certain lower temperature. It then changes into compression, its magnitude increasing rapidly as the temperature falls to room temperature. These changes of stress will easily be understood from Fig. 8. In approaching room temperature the temperature of the whole specimen becomes nearly uniform, and hence the thermal stress vanishes. By virtue of the above stress the inner portion undergoes a tension from the outer portion; this outer portion also exerts a tension to the outmost portion of the specimen by the strain

exerted in the foregoing sections. The result is that the intermediate layer exerts on both sides large tension; if it be sufficiently large, cracking of the specimen may take place in the vicinity of room temperature. Thus the nature of the stress present in small and large cylindrical specimens which are quenched in water may conveniently be illustrated in Fig. 9.

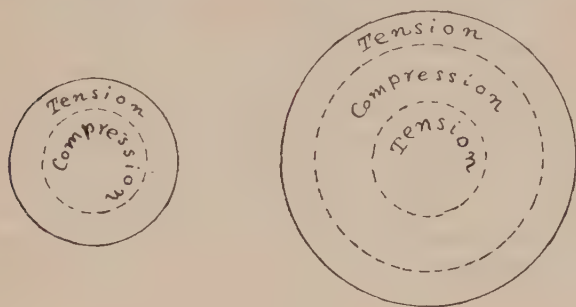


FIG. 9.

SUMMARY.

The result of the present investigation may be summarised as follows :

1. In a quenched steel a certain amount of austenite is generally present intermingled in martensite. The amount of this austenite increases as the quenching temperature increases.

2. In small pieces of steel the periphery is harder than the central portion only when the quenching is very soft. In a moderate quenching the hardness is everywhere nearly equal, but in a hard quenching the periphery is always softer than the interior. This anomalous phenomenon is explained by the presence of the arrested austenite in martensite.

3. The quenching cracks in small pieces of steel occur when the hardness in the central portion is much greater than in the periphery. The cause of the cracking is attributed to the stress caused by the difference in the specific volumes of austenite and martensite; the specific volume of the former structure being much smaller than that of the latter the central portion exerts

a large tangential tension on the periphery, causing thereby the cracking of the specimen.

4. Since the difference in the specific volumes increases as the temperature falls, the cracking usually takes place when the temperature of the quenched specimen approaches room temperature.

5. In a hard quenching, the hardness generally increases with the lapse of time, owing to a gradual transformation of the arrested austenite into martensite.

6. In the case of a large specimen, cracking may take place in the A1 range, and also in the vicinity of room temperature. The cracking at the high temperature is chiefly caused by the stress due to the structural difference between the inner and outer portions—pearlite and austenite—just below the A1 point; that at room temperature is due to a similar stress as in the small specimens.

DISCUSSION.

Professor ARNOLD, F.R.S., Member of Council, called attention to Professor Honda's reference to the presence of austenite. Austenite had been defined by Osmond as occurring only in supersaturated steels. To him (Professor Arnold) austenite was a solid solution of the carbon of supersaturation in the hardenite. Yet in the paper Dr. Honda had referred to it as though one had austenite, which as he (the speaker) said was a solution of FeC_3 in hardenite, which was a hardened saturated steel, and in unsaturated steels there could be no such thing as austenite, in his opinion. He would like to send in further remarks on the paper in writing. It was a very important paper, and was of considerable value. There were many matters in it which no doubt would be discussed, and he was extremely sorry to feel it his duty to have made a somewhat adverse criticism. Nevertheless, he fully appreciated the enormous amount of patient work which it had involved, and the thorough manner in which it had been done, at the same time without ascribing any very great value to it.

Dr. W. H. HATFIELD (Sheffield) said he could not completely agree with the authors, particularly as to Conclusion 1 of the Summary—that in all carbon steels after quenching there was more or less a proportion of austenite present. He thought the original austenite had ceased to exist in carbon steels when they arrived at ordinary temperatures after quenching.

CORRESPONDENCE.

Dr. A. McCANCE (Glasgow) wrote that Professor Honda had imagined the conditions of quenching in rather a different manner from that which actually took place. The stresses caused by quenching and due to what could be called "temperature gradient stresses" did not leave only small residual stresses at ordinary temperatures after the operation; on the contrary, the stresses left were quite considerable. During quenching the temperature gradients reached high values and they led to stresses which were above the elastic limit of the material, for the elastic limit diminished as the temperature was raised. Thus the metal at high temperatures was stretched and permanently deformed, and on cooling down reversed stresses were left which compared with the stress which had caused the deformation, and the work of Portevin showed how surprisingly great the intensity of such stresses could be. Iron was not by any means the only metal in which they

were formed; copper, silver, and gold were equally subjected to their effects when quenched, although these metals had no change points to cause interference. It was true that if the stress during cooling was everywhere below the elastic limit, then on returning to normal temperature the material would be once more free from stress at the lower temperature, but such was not actually the case, and when stretching of the outer portion took place the conditions were completely altered.

As for those cases where cracking took place some time after the object had been removed from the water, he believed that the majority of them were due to the fact that the metal when it had been removed from the quenching bath was not yet uniform in temperature, but was slightly above the temperature of the water at the centre. The gradual evening-up of the thermal conditions was sufficient to just cause the extra stress which led to cracking. There was another cause which brought about after-cracking in high carbon steels, and that was the excess γ -iron which was retained by the quenching above that necessary to retain the carbon as a solution. This γ -iron reverted gradually to α -iron, and caused in the process its corresponding volume change, the rate of reversion depending on the external conditions. The volume change might be sufficient in certain cases to produce cracking stresses, but after-quenching cracks were not of very frequent occurrence.

It would be necessary, however, to separate the causes predisposing to cracking and the causes leading to the stresses which formed the cracks. For instance, the crystal grain size had a very decided influence, and the larger the grain size the more easily were cracks produced. Taking a steel with 1 per cent. carbon and heating to 800°, no cracks would be formed if the piece were quenched after five minutes at that temperature, but if it were kept for three hours at the same temperature and then quenched it would be cracked every time. In that case the thermal stresses were the same, but the larger crystal grain size increased very greatly the liability to crack.

The factors causing cracking were really very diverse and were not by any means covered by the explanation given by Professor Honda. He deduced for instance, from his theory that there was a tension stress in the outer rim of a quenched bar, whereas actually it was the opposite which was true, as actual measurement (not yet published) had demonstrated.

With regard to the gradual increase in hardness of a quenched bar with time he (Dr. McCance) was led to examine that same point some time ago and he could confirm the observations recorded in the paper but he could not confirm that it was due to the transformation of austenite to martensite. If that were correct, why should it be equally evident in a steel with only 0.15 carbon as he had found, or in a 0.28 carbon steel, as given in Fig. 6, where the presence of excess austenite was not possible? It was found with a similar time duration in cold-worked iron, and he (Dr. McCance) considered it was due to an apparent

effect caused by the recovery in the elastic limit after deformation. It was another confirmation of the presence of high internal stresses. In high carbon steels quenched from a high temperature there was undoubtedly a gradual increase in hardness with time caused by the transformation from γ - to α -iron of the excess austenite, but that was a very slow change and took about four months for its completion, the hardness curve being almost a straight line over that period with a very gradual rise.

Although there was no denying the interest of Professor Honda's paper, he thought it would be necessary for him to revise some of his views on the question of cracking.

Iron and Steel Institute.

SOLID SOLUTION OF OXYGEN IN IRON.

By DR. J. E. STEAD, F.R.S.

WITH the advent and use of the cupric reagent of Rosenhain and Haughton, Stead, Whiteley, Humfrey, Le Chatelier, Dupuy, and others, the micro and macro study of the structures of iron and steel have passed into a new phase, and evidence is accumulating that many solid solutions of iron and every other element are electro-positive to pure iron.

Phosphorus, nickel, copper, cobalt, tin, antimony, silicon, chromium, carbon, &c., when in solid solution in iron, are of that character, and when placed in juxtaposition with pure iron remain white on being feebly attacked by a cupric reagent.

A most sensitive reagent of the many now in use is that of Le Chatelier and Dupuy. This consists of :

Alcohol (95 per cent.)	. . . . .	100 c.m.
Water	. . . . .	10 „
Cupric chloride.	. . . . .	1 gramme
Picric acid	. . . . .	0.5 „
Hydrochloric acid	. . . . .	1 to 3 c.m.

The most recent and important discovery following the use of reagents of this type is that made by Le Chatelier and Bogitch. It appears to prove (what had long been disputed), that iron could and did alloy with oxide of iron to form solid solution; that such alloys relatively to pure iron resisted the attack of alcoholic cupric solutions, copper being deposited on the latter more readily than on the former.

Although not disputing the findings of these investigators, the author had repeatedly failed to reproduce their results by burning pure electro-iron on a magnesia-lined base in oxygen in such a way that buttons of fused iron were obtained covered by thick layers of cinder. That the buttons were highly charged with free oxide was evident when examined under the microscope, for it appeared in the form of minute black globules.

On polishing and staining with all available cupric reagents the copper always deposited evenly over the surface, and on

dovetailing into the specimens strips of the original electro-iron and polishing and copper staining the two surfaces again the copper deposited equally on each. It is evident, therefore, that oxide may, and may not, under very slightly varying unknown conditions, remain in solid solution in iron. The following data afford what appears to be evidence of conditions favourable to the retention of oxide in solid solution.

The author long ago noticed that strips of electro-iron, after heating to 1000° C. in air and removing the scale, were sheathed with a film of finely crystalline iron covering an interior mass consisting of large crystals. On grinding off the fine-grained film so as to expose the coarser-grained material below and using this as an element of a voltaic cell, the second element being another piece of the strip from which the film had not been removed, and dilute HCl being the electrolyte, the needle of a galvanometer was strongly deflected in the direction which proved that the outer film was electro-positive to the metal below—in other words, that the film was the less readily attacked by the reagent. On applying a cupric reagent to the surface of a similar strip partly denuded of the film, copper was deposited less rapidly on the film than on the portion freed from the external skin.

These observations naturally led to the hypothesis that when iron is oxidised in air so as to produce an oxide scale, a minute quantity of oxygen passed coincidentally into the iron, forming a solid solution.

The experiments were repeated on several specimens of commercial soft steel, and in all cases an external film of metal resistant to cupric reagent attack was formed.

Previously the author had found that gases, &c., passed with greater facility into iron along the intercrystalline junctions of the crystals. For instance, from polished specimens which had been heated in air so as to form an adherent scale, on removing the scale when cold the junctions of the crystals were found to be channelled, showing that oxygen had been the more active at the boundaries of the crystals.

Bearing on this distinctive property of the intercrystalline junctions, when phosphide of iron diffuses into iron it travels for the greater distance along the junctions, as illustrated by



FIG. 1.
Junction at a weld in soft steel.
Etched by a cupric reagent.
 $\times 50$.

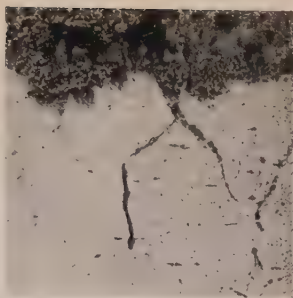


FIG. 2.
Oxidised steel plate showing
scale at top, steel below, with
intergranular oxides and globular
inclusions. Etched by dilute
acid. Vertical section. $\times 50$.



FIG. 3.
Same as Fig. 2—Horizontal
section. The continuous black
line is a fracture showing inter-
granular brittleness. $\times 50$.

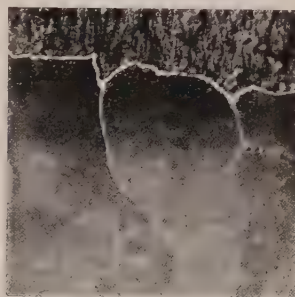


FIG. 4.
Another section of Fig. 2, etched
by a cupric reagent showing
white resist lines between the
crystals. $\times 50$.

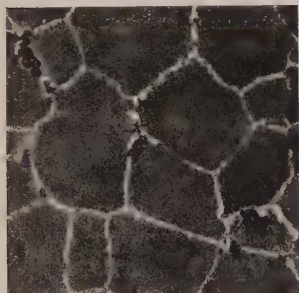


FIG. 5.
Horizontal section of Fig. 4,
just below scale, cupric etched,
showing white resist lines round
the crystals. $\times 50$.

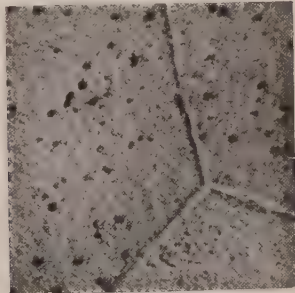


FIG. 6.
Part of Fig. 5 after long etching
and repolishing, showing junc-
tions of crystals in slight relief.
 $\times 350$.

the photomicrograph No. 31 (Plate XXXVI.) in the author's paper published in the *Journal of the Iron and Steel Institute*, 1915, No. I.

Mr. W. H. Cathcart first drew attention to the fact that on applying a cupric reagent to a cross-section through a weld of soft steel, a white resist line appeared at the junction of the two surfaces—an observation frequently confirmed. This Mr. Cathcart attributed to segregation of some of the phosphides when at welding temperature, but it may be due to more than one cause (Fig. 1, Plate XVI.).

An example of extreme brittleness in a steel, due to many years' heating in an oxidising atmosphere, has recently been supplied to the author by Mr. J. H. Harrison. It was taken from the lower portion of the steel casing of a heating stove at the Lackenby Ironworks and was thickly coated on each side with an adherent iron scale. On examination it was found to be brittle, due to feeble coherence between the crystals near the surface. On applying transverse shock, fracture commenced as intercrystalline and continued below the surface through the crystals. On making a section through both scale and steel, the reason for the way in which the fractures started was at once revealed, for veins of oxide of iron completely separated the crystals on the surface layers, as is shown in Fig. 2, Plate XVI. For a distance of about $\frac{1}{2}$ millimetre from the surface below the cinder there was a multitude of separate minute globular inclusions varying in diameter.

On sectioning horizontally through this layer and polishing, the oxide could be traced more or less continuously round the crystals (Fig. 3, Plate XVI.). On bending the section so as to put the polished surface in stress, fracture travelled round and never through the crystals. The dark continuous line in Fig. 3 represents the fracture.

On etching a polished section with a cupric reagent a layer or film of iron just below the cinder resisted the attack, and where there were oxide veins running downwards into the metal the iron adjoining the visible veins also resisted the attack, but what is even more remarkable is that below and beyond the ends of the visible veins of intercrystalline oxide of iron, the junctions remained white, resisting the reagent (Figs. 4 and 5, Plate XVI.).

Assuming the hypothesis to be correct that previous to the actual formation or separation of free oxide there is formed a solid solution of oxygen in the iron, we are forced to conclude that oxygen has travelled between the grains producing first solid solutions at the junctions, and that in course of time as more oxygen penetrated these became supersaturated and free oxide then precipitated and appeared as detached globules and later as continuous layers. On examining the surfaces of the fractures that passed between the grains many of them were found to be covered by fine dark spots, evidently corresponding with the globules of oxide of iron apparent in the polished section.

In order to determine whether the globular inclusions in the body of the crystals were oxide of iron, a polished section was heated in hydrogen gas at 1200°C . The result indicated that although they appeared to have been reduced in size they still remained.

The free oxide of iron veins were reduced, and there were no longer resisting areas along their borders, suggesting that the original white parts were due to oxygen in solid solution.

The analysis of the sound portion of the steel sheet was as follows :

	Per Cent.
Carbon	0·025
Manganese	0·539
Silicon	trace
Sulphur	0·040
Phosphorus	0·007

The remarkable feature in this analysis is the very low amount of phosphorus. The question at once presented itself as to whether it was not originally much higher but had diffused to the outside and become oxidised. If that were the case the phosphorus would be concentrated in the scale. This scale was therefore very carefully analysed, but there was no such concentration. The globular inclusions in the body of the crystals were subjected to careful examination. It was noticed on the surface after careful polishing they had the same dove-grey colour as larger inclusions of manganese sulphide originally present and were quite different from the iron oxide globules between the grains. Direct sulphur prints obtained by pressing the polished surface upon an acidulated sensitised dry plate or

bromide paper indicated that they contained sulphide, but what appeared to be iron oxide also gave sulphur stains. Judging, however, from the colour it was concluded that the minute dove-grey globules consisted mainly of manganese sulphide although possibly associated with FeO and MnO . The stains given by the oxide veins and globules led to the determination of sulphur in the thick exterior scale, and 0.8 per cent. of sulphur was actually found. It was a surprise to find so much, and it is evident that it must originally have been present in the blast-furnace gas.

How did the sulphur penetrate into the inside of the crystals of iron, and what must have occurred for it eventually to combine and segregate with the manganese? Beyond the facts, at present only conjecture is possible, and definite conclusions await further research.

SUMMARY.

Although much more research is necessary before definite conclusions can be formed, the results appear to indicate that :

1. When iron is heated in air or oxidising gases, apparently the surface layers absorb oxygen which passes into solid solution.
2. When supersaturated the oxide falls out of solution, forming separate globules of free oxide. These globules then become larger and larger as oxidation proceeds, eventually joining together to form continuous layers.
3. Oxidising gases find the most facile passage into the steel between the crystals. The gradual changes from solid solution to free oxide can be clearly traced along the oxidised junctions.
4. Sulphur, possibly as sulphurous acid (SO_2), in the gases penetrates into the body of the crystals, producing sulphide of manganese and possibly protoxide of manganese, which appear in globular form.

In conclusion, the author wishes to acknowledge the assistance of Mr. J. H. Harrison, Mr. Nicholson, Manager of the Lackenby Ironworks, Mr. J. H. Whiteley, Dr. T. Baker, and Mr. T. F. Russell in checking the microscopical observations, and that of his own assistants for their help.

Iron and Steel Institute.

CUPRIC ETCHING EFFECTS PRODUCED BY
PHOSPHORUS AND OXYGEN IN IRON.

By J. H. WHITELEY (STOCKTON-ON-TEES).

THE use of cupric reagents by metallographists for etching plain carbon steels, in order to detect structural heterogeneity, has developed to a considerable extent during recent years. Quite a number of these reagents have from time to time been suggested, and while, in certain cases, some may be more suitable than others, there is no doubt that they one and all reveal the same structure when applied to the same specimen. Certain parts are attacked to a greater extent than others, and contrasts are thereby obtained which are intensified by the deposition of a film of copper on the areas most deeply etched.

At first, the structural differences revealed were attributed to an uneven distribution of phosphorus in the steel, and the more resistant parts were considered to have a higher phosphorus content than the less resistant. This explanation has been challenged recently by Le Chatelier and Bogitch,¹ who state that it is not phosphorus but oxygen, in solid solution, which really gives rise to the effects. Others have since arrived at the same conclusion, amongst whom may be mentioned McCance,² who regards the micro-ghost lines in steel plates as due to dissolved oxide; also, Allison and Rock³ state that Stead's reagent attacks parts poor in oxygen.

The present investigation on this subject had two main objects in view: (1) to determine whether or not the cupric reagents will detect small variations of the phosphorus content only, synthetically produced in samples of electrolytic iron; (2) to endeavour to produce in iron samples variations of the oxygen content only, which could be detected by the cupric reagents. The method used is, in part, an adaptation of one

¹ *Revue de Métallurgie, Mémoires*, 1919, vol. 16, pp. 129-139.

² *Journal of the West of Scotland Iron and Steel Institute*, vol. xxvii. p. 38.

³ *Chem. and Met. Eng.*, 1920, vol. xxiii. pp. 383-389.

devised by Dr. Stead¹; it consists, in the former case, of phosphorising thin strips of the metal in hydrogen and then welding together a pile, consisting of alternate strips of phosphorised and non-phosphorised material, to form a composite piece in which the phosphorus content alone varied, so that the effect of known variations could be ascertained. A similar method has been employed in the endeavour to obtain an uneven distribution of oxygen.

Cupric Reagents used.—Throughout the present work the four reagents named below have been used :

- (1) Rosenhain and Haughton's² reagent.
- (2) Stead's reagent.³
- (3) Chatelier and Dupuy's reagent.⁴
- (4) Whiteley's reagent.⁵

These all contain a small amount of copper, but otherwise differ very considerably in composition. Notwithstanding such differences, it may at once be said that these reagents have all been found to behave similarly when applied to the specimens described below; the same areas in each specimen resisted the attack. The effect produced by one reagent could thus be confirmed by the others, and, in the preparation of the photo-micrographs, that reagent was used which gave the most suitable contrast.

Method of Phosphorisation.—The electrolytic iron used in the following experiments was in the form of a sheet $\frac{1}{30}$ inch thick. It contained 0.005 per cent. of phosphorus, and in other respects its purity was quite up to the usual standard for this material. To prepare a phosphorised sample, a piece 1.5 inches square was first cleaned in dilute hydrochloric acid, and then, after being carefully washed and dried, was rolled up loosely until it would readily pass down a tube of $\frac{5}{8}$ inch internal diameter. The roll was made loosely so that the gases, during phosphorisation, could easily reach all parts of the surface.

A piece of red phosphorus, weighing slightly more than the

¹ *Journal of the Iron and Steel Institute*, 1915, No. I. p. 165.

² *Ibid.*, 1914, No. I. p. 515.

³ *Ibid.*, 1918, No. I. p. 408.

⁴ *Comptes Rendus*, 1917, vol. clxv.

⁵ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 361.

amount required to give the desired percentage in the sample, was placed at the bottom of a clean dry tube of transparent silica 11 inches long and the above internal diameter. The roll of iron was next inserted about one half way down the tube, which was held horizontally. A cork containing a short delivery tube and an exit tube was then tightly fitted in, the delivery tube connected with a hydrogen supply and the exit tube with an air pump and pressure gauge. The hydrogen required was prepared in a Kipp's apparatus, by dissolving pure zinc in hydrochloric acid, and the gas was purified and dried by passing it through a U-tube, one limb of which was filled with strongly ignited lime and the other with phosphorus pentoxide. A small bulb containing ignited asbestos was placed between the U-tube and silica tube to prevent any phosphorus pentoxide being carried by the hydrogen into the latter.

The U-tube and silica tube were now exhausted, and when the rubber connections had been found to be air-tight, hydrogen was allowed to enter slowly. After this operation had been repeated three times the rate of flow of the hydrogen was increased, the air pump was disconnected, and an Arnold's bulb, holding a little strong sulphuric acid, was quickly attached to the exit tube, a rapid flow of hydrogen being maintained until it was certain that all the air had been swept out of the inlet tube of the bulb. The flow of gas was then slackened to a rate of about two bubbles per second, and, after a few minutes, the end of the silica tube was inserted in a small horizontal electric furnace which had previously been heated to about 1000°C . As soon as the phosphorus had vaporised the flow of hydrogen was stopped by closing the exit tube of the Arnold's bulb with a rubber stopper. The silica tube was immediately tilted to allow the roll of iron to slide to the bottom, and was again placed in the furnace. The vaporised phosphorus quickly combined with the surface metal and the phosphide so formed began slowly to diffuse inwards, the iron being thus "case-hardened" with phosphorus under conditions which precluded contamination with any oxygen.

After the specimen had been heated for about thirty minutes the tube was withdrawn from the furnace and allowed to cool. The metal was always perfectly clean and bright after this treatment. Any marked unevenness in the distribution of the

phosphorus over the surfaces could at once be detected by the brighter and smoother appearance of the skin where a heavy concentration of the phosphorus had occurred. With a little practice, however, this difficulty was largely overcome and a uniform surface obtained. Strips cut from different parts of the piece were then found to have approximately the same phosphorus content. The appearance of a cross section of a phosphorised piece, at this stage, is seen in Fig. 3, Plate XVII. ; the specimen was etched with reagent (4) and the degree of penetration of the phosphorus is plainly shown.

The next step was to bring about an even distribution of the phosphorus across the piece. It was again rolled up and placed at the bottom of the silica tube. The tube was exhausted and filled, this time with dry nitrogen, in the manner previously described. The end was then inserted in a small horizontal Méker furnace and maintained at a temperature of at least 1300° C. for two hours, during which period the pressure of nitrogen in the tube was kept a little above that of the atmosphere. On removal of the specimen after this treatment, the surfaces were still bright and untarnished. When etched cross sections were examined the effect seen in Fig. 3 could no longer be observed ; the distribution of the phosphorus now appeared to be uniform in samples containing up to 0.10 per cent., but above this amount a somewhat longer heating was usually required before the etching reagents failed to reveal any unevenness.

For the purpose of the present investigation, four pieces of the electrolytic iron were phosphorised to different degrees in the above manner ; the amount of phosphorus then present in each is shown in the table below. A piece of the material (sample No. 1) was also subjected to precisely the same treatment, but without the addition of any phosphorus, and these five pieces thus formed a series of samples in which only the phosphorus contents varied.

Table showing the Percentage of Phosphorus in the Prepared Samples.

Sample No.	Phosphorus per Cent.
1	0.005
2	0.023
3	0.045
4	0.070
5	0.130

EXPERIMENTS ON THE UNEVEN DISTRIBUTION OF PHOSPHORUS.

1. Two strips ($\frac{1}{2}$ inch by $\frac{1}{4}$ inch) of sample No. 4 and three of sample No. 1 were placed one above the other so that the small pile thus formed consisted of alternate layers of the two samples. The pile was tightly bound at both ends with a piece of very thin iron wire, and the strips were then welded together in an atmosphere of dry hydrogen by the following method.

A steel tube, 10 inches long and $\frac{5}{8}$ inch internal diameter, closed at one end, was made by boring a $\frac{7}{8}$ inch round containing carbon, 0.03; silicon, trace; phosphorus, 0.006; sulphur, 0.015; manganese, 0.31 per cent.¹ The tube was fitted with a cork containing a long delivery tube and short exit tube, and the inside wall of the closed end was thoroughly cleaned at a bright red heat by passing a slow current of dry hydrogen through the tube for about twenty minutes. When cold again, the tube was held horizontally and the pile was carefully placed at the closed end. In order to fix the pile in position, the ends of the two wires used for binding were made to serve as weak springs, and were cut down until the pile could be pushed along the tube with the application of a little pressure. The cork, now containing a short delivery tube, was again inserted, and when connections had been made with the hydrogen supply and pump, the tube was filled with dry hydrogen in the manner previously described. The pump was then disconnected, an Arnold's bulb attached as before, and a slow current of hydrogen allowed to pass through the tube for about thirty minutes to ensure the complete removal of all air. The end containing the pile was then placed in the horizontal Méker furnace, which had previously been raised to about 1350° C. As soon as the tube had attained this temperature, a rapid flow of hydrogen was started; the Arnold's bulb was immediately disconnected and quickly replaced by a glass stopper. The rubber tube attached to the delivery tube was next tightly clipped and the hydrogen apparatus removed. The tube, thus filled with hydrogen and sealed, was then withdrawn, care being

¹ All the steel cylinders used in the present investigation were made of this material.

taken to keep the pile in a horizontal position, and the heated end was quickly hammered down on the anvil to a short bar about $\frac{1}{5}$ inch thick.

When a polished section of the bar was etched with picric acid, the welded area could readily be seen without the aid of the microscope. On etching with a cupric reagent, the composite nature of this area was at once revealed. The two layers of the phosphorised sample resisted the attack of the reagent much more than the other three and stood out in marked relief. Fig. 1, Plate XVII., shows the effect obtained with this specimen when reagent (2) was used. The several layers of the pile had apparently welded together perfectly, for reagent (4) showed that crystallisation had taken place across the welds at all parts. Since the two samples of which the pile was made had received the same treatment in every respect, except that 0.065 per cent. of phosphorus had been added to one and not to the other, the experiment afforded clear evidence that the cupric reagents were capable of detecting the presence of small amounts of phosphorus, in solid solution, when unevenly distributed in iron of an otherwise high degree of purity.

It seemed desirable, however, to confirm this result by first removing any small quantity of oxygen which might be present in the original electrolytic iron. A piece of the material was, therefore, again phosphorised to the same extent as before (0.07 per cent.), and was then heated, together with a piece of the original iron, in a current of dry hydrogen, at 1300° C., for two hours. Any oxygen present in the samples should thereby have been removed. A second pile was made of strips from these two samples and welded in hydrogen as before. The phosphorised layers in the etched section were again clearly revealed by the reagents; the use of hydrogen, instead of nitrogen, in the heat treatment made no apparent difference. Consequently, it seems reasonable to conclude further that the cupric reagents will detect an uneven distribution of small amounts of phosphorus in iron entirely free from dissolved oxide.

2. In this experiment a pile was made containing three strips of the original untreated iron and two of sample No. 5, arranged alternately; above these were placed five strips of the former material only. The pile was welded in dry hydrogen, as in the

previous experiment. Very strong contrasts were here obtained when the cupric reagents were applied to the polished section—in fact, the two phosphorised layers could readily be detected with ordinary alcoholic solution of picric acid. On the other hand, the five layers of original material could not be distinguished by any of the methods of etching, and this part of the pile now appeared to be one homogeneous piece of metal. Fig. 8, Plate XVIII., shows this area after etching with reagent (4); on the left, one of the phosphorised layers is seen, but in the large area on the right no indication of any of the weld junctions can be observed. As far as could be judged from microscopic evidence, a perfect weld had been obtained by welding in an atmosphere of dry hydrogen. This subject will be again referred to in the next section, when dealing with the effect of the presence of oxygen in welding.

A section of the welded pile was heated *in vacuo* at 1050° C. for one hour. This was done simply with the object of noting the manner in which the phosphorus diffused. The result is seen in Fig. 4, Plate XVII.; a considerable amount of diffusion had occurred, as is indicated by the narrowness of the dark band of the original unphosphorised iron, which, before this treatment, was of the same thickness as the phosphorised layers. Moreover, the phosphorus is not advancing uniformly, the manner of its diffusion being reminiscent of a similar effect obtained by Dr. Stead in one of his experiments.¹

3. With a view to obtaining some idea of the least difference between the phosphorus contents of two adjacent parts which the cupric reagents would detect, a pile was prepared consisting of a strip of each of the four phosphorised samples and five strips of the original material arranged alternately and in order of the phosphorus percentages. The pile was fixed inside a small cylinder, made by drilling a hole, 1 inch deep and $\frac{1}{2}$ inch diameter, in a short piece of the steel bar. The cylinder was tightly closed by driving into it a plug of the same steel, and was then placed in the furnace at a temperature of 1300° C. or thereabouts. A small quantity of air, which would measure about 3.0 cubic centimetres, was, of course, enclosed; but, as the temperature rose, the greater part of the oxygen present

¹ *Journal of the Iron and Steel Institute*, 1915, No. I., Plate XXXVI. No. 31 (b).

would quickly unite with the exposed surfaces of the pile and cylinder, so that the pieces themselves would actually be welded in nearly pure nitrogen. In three minutes the cylinder had attained the furnace temperature ; it was then withdrawn, placed on the anvil, and hammered down to a bar $\frac{1}{5}$ inch thick.

The appearance of a section, after etching with reagent (1), is seen in Fig. 5, Plate XVII. ; the band on which the least amount of copper has been deposited is that of sample No. 5, containing 0.13 per cent. of phosphorus. As the phosphorus content of the alternate strips decreases the contrasts become weaker, but even where the phosphorus difference is only 0.018 per cent. it is still clearly revealed by the reagent.

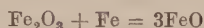
In order to test the effect of a difference of 0.02 per cent. in material containing a higher average phosphorus content, another similar experiment was made in which alternate strips of samples Nos. 2 and 3 were welded together. Fig. 2, Plate XVII., shows the result obtained by the application of reagent (3) to the polished section. Here, also, the contrast is quite satisfactory. The above experiments thus afford evidence that differences of less than 0.02 per cent. between the phosphorus contents of two adjacent parts can readily be detected by the cupric reagents. This conclusion has since been confirmed in several experiments, but whether an equally small variation is revealed where the average phosphorus content is much higher, has not yet been ascertained.

EXPERIMENTS ON THE UNEVEN DISTRIBUTION OF OXYGEN.

The experimental results obtained in the preceding section prove that heterogeneity in iron, as revealed by the cupric reagents, may be produced by an uneven distribution of very small amounts of phosphorus only. In the present section, some experiments are described which were made with a view to ascertaining the etching effect produced by an uneven distribution of oxygen, while that of the phosphorus remained uniform.

4. Several strips of the electrolytic sheet were put into a small steel cylinder and closely packed with finely powdered oxide of iron. This oxide contained 26.0 per cent. of ferric

oxide, and was prepared by oxidising a quantity of the electrolytic iron in an electric muffle. The cylinder was tightly plugged and then placed at the bottom of a strong silica tube. Having exhausted the tube, the end was inserted in a horizontal Méker furnace and kept at a temperature of from 1300° C. to 1400° C. for two hours. On opening the cylinder, it was seen that the oxide had been in a fluid or partly fluid condition, for it had fused into one solid mass. An analysis now showed it to contain only 8.0 per cent. of ferric oxide. The reaction



had consequently taken place, but had not proceeded to completion. Yet it is very probable that equilibrium had been reached, because in a number of similar experiments practically the same percentage of ferric oxide remained, although the initial quantity was varied considerably and also the period of heating.

The oxide adhering to the strips was now carefully removed and the phosphorus content of the iron again estimated. It was still found to be 0.005 per cent., no alteration having occurred. Sections of the material, under the microscope, were seen to contain quite a number of globular oxide particles which would in all probability have the same composition as the exterior oxide and contain, therefore, 8.0 per cent. of ferric oxide. Whether these particles had worked their way into the iron at the high temperature used, or had separated from solid solution as the metal cooled, has not been ascertained. On account of these inclusions, however, it was impossible to determine by analysis the amount of oxide which was now dissolved in the iron. It was nevertheless of interest to see how this presumably oxidised iron would behave towards the cupric reagents when welded with the original material. A pile consisting of several alternate layers of the two was therefore prepared and welded together inside a small tightly plugged steel cylinder, as in experiment (3). Fig. 6, Plate XVIII., shows the appearance of a section of the weld when etched with reagent (2); thin white resist-lines¹ appear at the weld junctions only.

¹ This term has been suggested to the author by Dr. Stead.

Except for these, the reagent has attacked all parts equally, and no effect comparable even with that given by the least variation of phosphorus in experiment (3) has been obtained.

5. The author has shown, in a previous paper,¹ that Armco iron contains a considerable quantity of iron oxide disseminated throughout the metal in a fine globular form. These particles have most probably been precipitated from solution in the iron as the metal cooled from the molten condition; in any case, their presence justifies the conclusion that the iron itself is saturated with oxygen. It was also shown that when strips of the material $\frac{1}{350}$ inch thick were heated at 1300° C. for one hour in an atmosphere of dry hydrogen, the whole of the oxide particles were reduced, and the probability is that the oxygen in solid solution had also been entirely removed. The speed of deoxidation was found to diminish as the temperature was lowered and at 900° C. it was extremely slow. Armco iron thus appeared to be very suitable for the purpose of the present investigation, and use has been made of it in the following experiment, in which strips of the reduced and original oxidised metal have been welded together.

To remove the oxygen from the iron, a strip about 4 inches long and $\frac{1}{400}$ inch thick, containing 0.016 per cent. of phosphorus, was loosely rolled up and placed at the bottom of a tube made from the same piece of iron as the strip itself. A tube of the same material was used so as to avoid any serious alteration in the phosphorus content of the strip during the time it was to be soaked in hydrogen. In order to prevent the strip and tube welding together, the tube was held horizontally, and, before the roll was placed in it, a little powdered calcined magnesia was scattered over the bottom. The tube was fitted with a cork through which passed a long delivery tube of fused silica and short exit tube; connections were then made with the hydrogen supply and Arnold's bulb as in the previous experiments. A current of dry hydrogen was next passed through for an hour or so until it was certain that all air had been displaced. The end of the tube was then inserted in the Méker furnace and the strip heated in a very slow current of hydrogen at a temperature between 1300° C. and 1400° C., for two and a half hours.

¹ *Journal of the Iron and Steel Institute*, 1920, No. II. p. 143.

Excessive scaling of the tube was prevented by casing it in a sheath of sheet nickel.

The strip, on removal, was perfectly clean and, when sections were examined under the microscope, no oxide particles could be seen. Since one hour's heating at the above temperature had previously been found sufficient to remove all visible oxide, there can be little doubt that, in the present case, the strip had been deoxidised to the fullest extent possible in hydrogen.

Alternate layers of the deoxidised and original material were now made into a pile, which was then fixed in a thin-walled tube of steel and welded in dry hydrogen at a temperature not exceeding 900°C ., about ten minutes being required to heat the tube. This temperature was used because, in the short time of heating given, no appreciable reduction of the oxide particles in the strips of original material would then take place, and also because it is below the melting point of the FeO-FeS eutectic which is present in the iron.

When etched with picric acid, the alternate layers of the original and reduced strips were readily distinguished in the section by the presence of oxide particles in the one and not in the other, as illustrated in Fig. 9. Application of the cupric reagents again failed to produce any effect comparable with that given by even small variations of the phosphorus content. Fig. 10 shows the appearance of the section after etching with reagent (2); the three darker bands, on which most copper has been deposited, are the original material, so that here the deoxidised material is actually the more resistant of the two. The striking feature, however, is the presence of the white resist-lines at the welded junctions, as in the previous experiment. Moreover, these invariably occurred at the margins of the original material, and were not present in the deoxidised layers. This was confirmed in a second similar experiment in which a pile was prepared containing three alternate layers of the two materials and then six layers of the deoxidised only. Resist-lines were again found at the margins of the original material, but were not present in that part of the welded pile which consisted entirely of the deoxidised layers.

The presence of these resist-lines was revealed by all the reagents. A typical instance of the effect given by reagent (4)

is seen in Fig. 7, Plate XVIII., which is a photomicrograph of one of the welds of oxidised and unoxidised electrolytic iron obtained in the previous experiment. Crystallisation has clearly taken place across the juxtaposed faces, since the resist-line which marks the junction passes through the crystals. Although complete welding has occurred, the result is not a perfect homogeneity of structure such as is shown in Fig. 8, Plate XVIII., which illustrates the effect obtained in experiment (3), where strips of unoxidised electrolytic iron only were welded together in dry hydrogen. In Fig. 8 no indication of any resist-lines is to be seen.

The inference to be drawn from these observations is plainly that the resist-lines are due, in some way, to the presence of oxygen in the iron, for there is every reason to believe that, if oxygen is completely eliminated, these resist-lines will not be produced. But, apart from this effect, the presence of oxygen in uneven distribution has not been found to yield, with the cupric reagents, effects similar to those given by even the smallest variation of phosphorus.

SUMMARY.

In conclusion, it may be remarked that the investigation here recorded must be regarded as chiefly preliminary in character. The method of synthetically producing heterogeneity of structure which has been used is one that appears capable of extension in several directions. Briefly, the two results which have so far been obtained are as follows :

1. Differences in the phosphorus content of less than 0.02 per cent. in adjacent parts of otherwise pure iron can be readily discovered by means of the cupric reagents ; as the difference is increased, at any rate up to 0.15 per cent., the contrast becomes more and more pronounced. These differences were produced by first phosphorising strips of the iron with phosphorus in hydrogen at 1000° C. and then welding, in hydrogen or other gas, a pile made up of alternate strips of phosphorised and unphosphorised material.

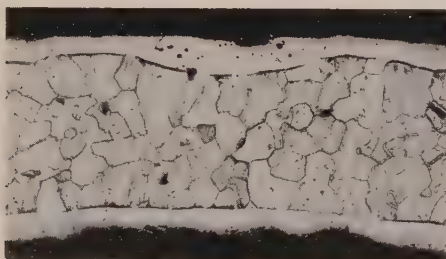
2. Attempts to produce, in a similar way, an unequal distribution of oxygen, which could be detected by the cupric reagents



No. 1.



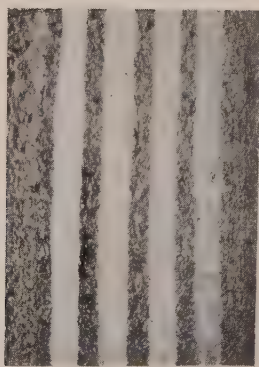
No. 2.



No. 3.



No. 4.



No. 5.

No. 1. Weld, P. 0.005 and 0.07 %, Stead's reagent. $\times 65$.

No. 2. Weld, P. 0.023 and 0.045 %, Chatelier and Dupuy's reagent. $\times 60$.

No. 3. Electrolytic iron sheet, case-hardened with phosphorus, Whiteley's reagent. $\times 60$.

No. 4. Weld, P. 0.005 and 0.13 % after 1 hour at 1050° C, Rosenhain's reagent. $\times 55$.

No. 5. Weld, P. 0.005, 0.023, 0.045, 0.07, 0.13 %, Rosenhain's reagent. $\times 60$.

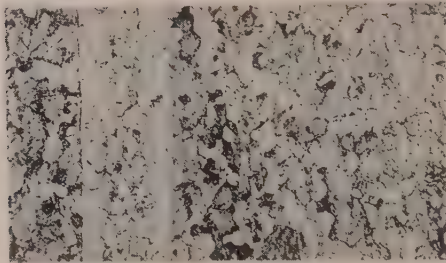
To face p. 288.



No. 6.



No. 7.



No. 8.



No. 9.



No. 10.

- No. 6. Weld, alternate strips of oxidised and pure iron, Stead's reagent. $\times 70$.
 No. 7. Same as No. 6, showing one weld only, Whiteley's reagent. $\times 400$.
 No. 8. Weld, one strip, P. 0.018 and rest P. 0.005 %, Whiteley's reagent. $\times 55$.
 No. 9. Weld, alternate strips of original and reduced Armco iron. $\times 180$.
 No. 10. Same as No. 9, Stead's reagent. $\times 70$.

in the same manner as that of phosphorus, have failed. When oxygen was present, white resist-lines were formed only at the weld junctions, but these resist-lines were not formed when unoxidised iron was welded in dry hydrogen. Two methods of obtaining an unequal oxygen content were used: (*a*) by soaking pure iron in its own oxide at a high temperature and then welding it with the unoxidised material; (*b*) by reducing highly oxidised iron in hydrogen and then welding it with the original metal at a low temperature.

The author has much pleasure in acknowledging his indebtedness to Dr. Stead, who has kindly examined many of the specimens here described, and confirmed, by means of his own reagent, the etching results depicted in the illustrations.

DISCUSSION.

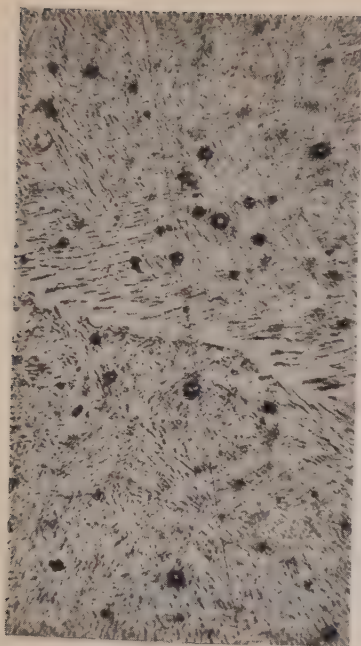
Mr. COSMO JOHNS (Sheffield) said the papers by Dr. Stead and Mr. Whiteley constituted a new departure in the way of looking at certain fundamental metallurgical questions. The President, with all his caution and long experience, asserted definitely that oxygen in some form or other was soluble in steel. There had been evidence to that effect accumulating for a considerable time. Having regard to the wealth of that evidence and to the support that it had received, the onus of proof in future discussions to the contrary would rest on those who took the opposite view. The work was not finished, because there still remained to be worked out the equilibrium diagram for iron and oxygen, a particularly difficult piece of work. He should expect that the eutectic might not be of oxygen and iron but of some oxide of iron and iron analogous to the equilibrium diagram so well known in copper where cuprous oxide and iron were related. He was not discussing so much the papers themselves, because they only proved what some had thought for many years, but one of the consequences that would flow from the papers was that there would now be discussed many well known but imperfectly understood defects in steel which caused very considerable difficulties to those engaged in practical work. There was a well-worn theory as to the cause of blowholes. It was asserted that the virtue of silicon when added to steel was to increase the solubility of the liquid steel for gases. That theory never would stand a moment's careful consideration. It was unscientific and in contradiction to other well-known facts, but it still held good with a large number of people. It found a prominent place in most of the text-books on metallurgy. If iron oxide were soluble in steel—and there could be no doubt about that after the work that had been done on the Continent and in England—there was another element in steel which was never analysed, that was always present, and that must be brought into discussion and into future consideration of the cause of blowholes. There were such things as other solid non-metallic impurities, chiefly silicates of manganese and sometimes oxide of aluminium. To those who made steels and who had to satisfy tests taken transversely, those things were very serious. He was not aware of any acceptable theory of the occurrence—not one that was generally accepted—but, if iron oxide were soluble in steel, one had a source for the oxygen, because those non-metallic impurities to which he had referred—those silicates—were oxides of silicon and of manganese in varying proportions. No one, so far as he remembered, had been able to give a convincing explanation why basic steel should give a lower tensile strength than acid steel of practically the same composition. Might he suggest to those who were

interested in the question—and probably there were many—that in the difference of the oxygen content of the two steels they might possibly find an explanation of that rather mysterious fact? There was also that particular defect—and it might be that in calling it one defect more than one thing was really involved—known as hair-lines, a subject which had given rise to more discussion on metallurgical subjects connected with steel than almost any other in recent times, especially on the Continent and in America. In America they were called “snowflakes,” because they occurred on transverse tests and appeared as bright circular or semi-circular patches on the test-piece and caused its failure. Those things too could be discussed in the light of the present knowledge that oxygen was soluble in steel. From the work done by Dr. Stead it would be noticed that Mr. Whiteley assumed, as he was quite entitled to do, the solubility of oxygen or of iron oxide in steel. Dr. Stead with great caution proceeded to demonstrate its solubility, but he spoke of the oxide of iron as being drawn to its solution owing to the fact that the steel was supersaturated. That at once showed that the solubility of oxide of iron in steel was a limited solubility, and that therefore during the cooling of the ingot the iron oxide would be concentrated between the crystals and in those parts which solidified last. It followed the general rule as to substances with limited solubility. As was known from work that had already been done with manganese up to the limits in which it was used in ordinary steel, in order to get limited solubility up to that range, the silicon too did not have limited solubility. There was therefore the case of a steel which might have been in equilibrium at a time when it was being poured into the ingot but in which during the cooling in the ingot the silicon and the manganese would remain distributed through the liquid steel or the solidifying steel, and the oxide of iron would be concentrating locally, and there could not then be any such state as equilibrium. There were then provided available conditions for a new set of reactions in which temperature played a considerable part, where the oxide of iron or silicon or manganese and the carbon were in a new state of relations. Reactions would be set up, and oxidation of either the carbon or the silicon and manganese, depending upon the concentration of each of those elements in the liquid steel, would occur. Gaseous and solid non-metallic impurities would then have been produced in that state.

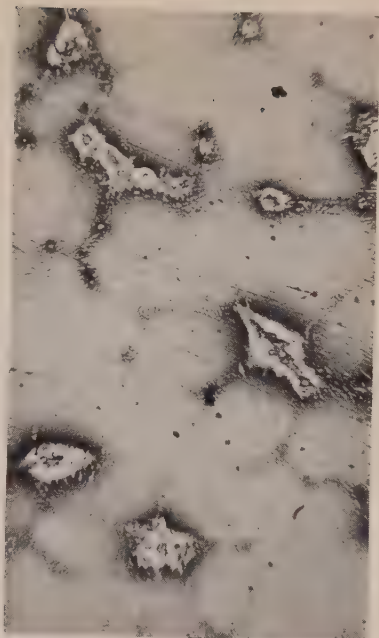
Professor ARNOLD (London) said that during the last decade of the last century, at a meeting at Stockholm at which the President was not present, he had read a paper on the microchemistry of cementation, in which he had put forward considerable evidence proving the absorption of oxygen by iron and the ultimate precipitation of the oxide. In cementing, an air passage sometimes formed through some fault at one part of the cement chest, which of course was filled with charcoal, and the charcoal in the vicinity of a certain bar

would be burned ; in fact, the ash of the charcoal would be found on that bar. The outside of such a bar was what was called "aired," and it was a very curious bar indeed. A full description of it would be found in the *Journal of the Iron and Steel Institute*, 1898, No. II. p. 185. Taking a section of an aired bar, the general composition in the middle of the bar was 1.4 per cent. of carbon. Then it dropped to 1.2 per cent., then to 0.32 per cent. of carbon, and then to 0.00 per cent. of carbon on the outside layer which had been aired. There was not a trace of carbon in it, but evidently it had become oxygenated. The oxygen had penetrated the pure iron area, and on the bar cooling it had come out in little dots which in many cases had segregated into alignments at the edge of the bar. A very carefully made drawing would be found in the *Journal* to which he had referred. It would be seen that it gave evidence of great weight that the oxygen evidently had actually dissolved in the bar and the oxide had precipitated out in that manner. As to the question of the recognition of reagents, particularly cupric reagents, referred to by the President, it was quite true what the President had said, that one had to be very cautious, because it must be remembered that the evidence obtained by that method of etching might be merely a question of the opposite electropositions which were known to be assumed by adjacent crystals identical in chemical composition but of varying orientations.

Dr. A. McCANCE (Glasgow) said he had approached the question of the solution of ferrous oxide in steel from a rather different standpoint than either the President or Mr. Whiteley. During the examinations of inclusions after etching it had been very noticeable in some cases that certain inclusions had a white halo round them, and they etched in a different manner from a great many of the other inclusions contained in commercial steels. On careful examination, all such inclusions seemed to belong to the oxide type, and it had occurred to him that perhaps the cause of that halo in etching was due to the presence of some dissolved oxide. If one of those samples were heated in hydrogen to about 1100°, the halo completely disappeared after half an hour's heating. If a steel containing a well-marked ghost-line were heated up in the same way in hydrogen at 100°, the ghost-line also completely disappeared after half an hour, pointing to some chemical reaction going on between the hydrogen and the steel which etched as a ghost-line or as a halo. A curious fact, which had always puzzled those who had tried to melt carbon steel in a vacuum, was that much of the carbon disappeared. If steel containing 0.5 per cent. carbon were melted in a vacuum furnace, practically the whole of the carbon disappeared and carbonless iron resulted. There was another fact, namely, that if, instead of melting, it were merely heated in a vacuum and the heating continued over a sufficiently long time, the steel became decarburised and ultimately left a steel containing, if not absolutely no carbon, a very much lower percentage of carbon than the original sample con-



No. 1.



No. 2.



No. 3. $\times 70$



No. 4. $\times 30$

Chatelier & Dupuy's reagent
used.

Chatelier & Dupuy's reagent
used.

Illustrating McCance remarks on Whiteley.

To face p. 292.

tained. But he had been assured by a very able investigator that if that same steel was carburised, it could be heated up in a vacuum and the carbon no longer disappeared. All those facts seemed to show that there was some oxide, probably iron oxide, in the steel which was reacting with the carbon. He believed that the gases which were given off when steel was heated in a vacuum were really due to the reaction between the carbon and the ferrous oxide or some other oxide in solution. However, the only means they had of controlling the ferrous oxide was by controlling the composition of the slag in the melting furnace. In a small electric furnace he had melted up various experimental samples and so controlled the slag that varying amounts of ferrous oxide could be obtained. The only way of controlling the ferrous oxide was to control the temperature. With that object he had adopted a method where the temperature of the hearth after tapping was measured accurately with an optical pyrometer immediately after the furnace was tapped and for a regular period at stated time intervals. A curve could then be drawn of the cooling of the furnace hearth, and by producing backwards the temperature at the time of tapping could be arrived at.

After the charge had been melted and the slag had been scraped off, a new slag was made with pure materials, which was allowed to stand at as constant a temperature as could be kept until equilibrium had been attained between the slag and the metal.

Samples were taken from steels at different temperatures and allowed to cool down slowly, after which they were etched in order to find out whether there was any difference with regard to the inclusion of oxygen. The etching reagent which he found gave the most distinct and clear result was a modification of one suggested by Dr. Stead, a saturated solution of picric acid, for he found that that reagent was considerably improved by the addition of one or two drops of hydrofluoric acid. The results which had been obtained could be illustrated by two photographs which showed very distinctly the difference in the oxygen content. At a temperature of 1740°C. , the slag contained roughly about 6.4 per cent. of FeO , and he could not detect, except for minute spots, any oxide inclusions or oxide etching in the sample (Micrograph No. 1, Plate XVIII A.). At lower temperatures, however, the results showed that the steel was full of inclusions, and around each of those inclusions there was a very dark etching area which he believed was due to the presence of dissolved oxide (Micrograph No. 2, Plate XVIII A.). It was certainly peculiar that it was only in the centre of such areas that the inclusions existed and in no other place was there any trace of inclusion. That seemed to point strongly to the fact that ferrous oxide was one of the main sources, if not the main source, of non-metallic inclusions.

He thought it could be taken as very certain from the confirmatory experiments of Mr. Whiteley and Dr. Stead that ferrous oxide did dissolve in steel. The fact that it was very difficult to obtain micro-

scopic evidence by welding methods could be explained by the fact that such oxide seemed to diffuse very slowly.

The PRESIDENT said there was no doubt that the oxygen question in steel was one of paramount importance. The effect of oxygen on the mechanical and physical properties of steel was not thoroughly known. There were a great many things which had to be taken into consideration, and therefore it would be very difficult to answer the questions which were almost certain to be put. It was for those who had research laboratories and opportunities of work to follow the question up, and he had no doubt that if that were done a good deal of valuable information would be obtained.

CORRESPONDENCE.

Professor H. M. HOWE, Vice-President, wrote that Dr. Stead's experiments on heating strips of electro iron, together with the discussion of the behaviour of Mr. Harrison's specimens, offered strong evidence that oxygen could dissolve in solid iron. Indeed the very fact that the conduct of the open-hearth and electric process had been based on an assumption to that effect, and that those processes had for a long time been conducted on that hypothesis, would in itself offer pretty strong evidence of the solubility of oxygen in iron. Therefore Dr. Stead's experiment at the opening of his paper, in which the cupric solution failed to distinguish between oxygen bearing and oxygen free iron, was to be interpreted as implying that the cupric solution was only a very rough test for the uniform distribution of oxygen, so rough as to fail to disclose the difference between the oxygen bearing and the oxygen free iron prepared in the special way followed by Dr. Stead. That was certainly surprising, because under the conditions which he gave rather a large oxygen content should have been expected in the oxygen bearing iron.

The results obtained by Mr. Whiteley appeared to confirm that inference, and thus to show that it was the true explanation of Dr. Stead's failure to find a difference in etching effect with cupric solution between the oxygen bearing and the oxygen free specimens mentioned on the first page of his paper.

Professor HOWE also sent in the following communication :

I here offer a tentative explanation of two important observations communicated to me by Dr. Stead in advance. They are :

1. That on heating a polished surface of iron in air at about 750° C., the grain boundaries are channelled.
2. That when soft steel is exposed to oxidising conditions for

years so that much of its total mass has been converted into oxide, the path of rupture of the remaining metal is intergranular, and the oxidation proceeds not only on the surface but also between the grains.

In short, the grain junctions are more readily attacked than the grains themselves, so that if this attack be greatly prolonged the degree of channelling and oxidation between the grains becomes so deep as to lead to an intergranular path of rupture.

The intergranular rupture is a natural consequence of the preferential intergranular oxidations. Does not this latter represent two things, first, the presence of amorphous metal between the grains, which would naturally be attacked by reagents in general faster than the crystalline metal, quite as a slag is dissolved far more easily than in its vitreous state, as when chilled in water, than when it has crystallised by slow cooling; and, second, the difference of potential between adjoining grains representing their difference of orientation?

Mr. J. H. WHITELEY (Stockton-on-Tees) wrote that some little time ago he made a simple experiment which bore directly upon the subject Dr. Stead had brought forward in his interesting paper. A short bar of mild steel (combined carbon, 0.2 per cent.) $1\frac{1}{2}$ inch square was drilled through longitudinally with a $\frac{1}{4}$ -inch drill in two places. The bar was then heated to a bright red and forged down to a piece $\frac{3}{8}$ inch thick. During the heating of the bar a coating of scale was, of course, formed on the walls of the two holes, and when an end section, cut from the forged piece, was polished and examined, the positions of the two holes were readily found by the presence of two narrow layers of iron oxide in the steel. The piece was next placed on the top of a steel slab, which was then lowered into a gas-fired slab pit and allowed to stay there for two hours at a temperature of 1300° to 1350° C. When the slab was taken out to be rolled the piece was removed and allowed to cool in the air. When sectioned and examined the position of the two holes could still be found, but no indication of the presence of white resist areas surrounding the oxide layers was obtained with any of the cupric etching reagents. Just beneath the scale on the outside of the bar, however, a white border was present after cupric etching as shown in Micrograph No. 3, Plate XVIIIa. There was no difficulty in reproducing that result by repolishing and re-etching, and apparently it was precisely the same effect as that described by Dr. Stead. The adhering scale was removed and analysed and was found to contain 0.60 per cent. of sulphur as iron sulphide, which, of course, had been derived from the gases, as must have been the case in Dr. Stead's sample. Since the cupric reagents failed completely to give any white border round the interior oxide layers, and yet gave a marked effect under the outer scale, the evidence here obtained seemed to indicate that the effect might be due to diffusion of sulphide as well as oxide into the steel. Until the same result had been obtained with pure iron and pure oxide of iron, a doubt must therefore exist as

to whether solid solution of oxide was alone responsible for the white resist areas as described by Dr. Stead.

It would be noticed that immediately below the white margin in No. 3 there was a very dark area where the heaviest deposit of copper had occurred. The same effect was also to be seen in photo No. 4 in the paper, and he (Mr. Whiteley) was rather surprised to find that Dr. Stead had nothing to say on that point. Did not the presence of that dark area strongly suggest that some constituent—oxide, sulphide, or whatever it might be—was not diffusing inwards but moving outwards and concentrating in the layer of steel just below the scale? The dark areas would then be those parts which had been most depleted of that substance.

In any case, he did not think the extent of the white areas indicated, even approximately, the distance to which the impurity had travelled into the steel. He arrived at that conclusion from a comparison of the depth of the white area in photo No. 1 with that found in a similar piece which had been heated for eighteen hours in the slab pit. If the resist area really marked the limit of diffusion, it should certainly have been much more extensive in the piece heated for eighteen hours than in that heated for only two hours; but, as a matter of fact, there was practically no difference in the width of the resist-lines in the two pieces.

Another experiment also pointed to the same conclusion. He cut several horizontal layers from a piece of the plate Dr. Stead had described, a sample of which he kindly gave him. Two layers containing the outside surface were then reduced in hydrogen at 700° C. for half an hour. That temperature was chosen because previous experiments had shown that the white resist areas were not removed by hydrogen below 900° C. in a short heating. He then made up a pile of the pieces in which the two reduced surfaces were placed together and also the surfaces of two interior sections. The pile was next placed in a small steel cylinder, which was then tightly plugged, heated to a bright red, and forged to a thin bar. When sectioned and examined the result shown in Micrograph No. 4, Plate XVIII A., was obtained with the cupric reagents. At the junction of the two reduced surfaces a broad white resist line was present, but at the junctions of the interior pieces no such effect was to be found. One of the welds of the interior pieces was seen near the letter A in the photo. Now the white area seen in the photo included the resist-lines which Dr. Stead had described, but it was at least twenty times broader. While it was not at all clear as to how that effect was brought about, it was nevertheless quite evident from the etching result that the steel just below the surface differed from that further inside. Presumably that difference was due to the presence of dissolved oxide, sulphide, or both absorbed from the outside scale. The point to note, however, was that the extent of the diffusion inwards of the impurity was not determined, as it would be in the case of phosphorus, by the boundary

of the white resist area shown by Dr. Stead, because the extent of the area could be greatly increased in the manner he had described above.

Dr. STEAD, in reply to Professor H. M. Howe's note, wrote that the fact that the junctions of the crystals of iron were attacked in advance of the body of the grains suggested either a certain amount of porosity between the crystals, or something the nature of which was unknown, and which had been suggested but not proved to be amorphous metal. It was not clear how difference in orientation or difference in electromotive force of adjoining grains could cause preferential attack at the junctions. It was not for a moment suggested that the cupric reagent was infallible in the detection of solid solutions of oxide in iron. What had been proved was that oxide of iron in solid solution (in certain degrees of concentration) was revealed by that reagent both in Mr. Whiteley's and his own work.

Mr. Cosmo Johns' statement that the work on the subject of oxygen in iron and steel was not finished was quite right. There was so much assumption unaccompanied by solid scientific fact that it was essential that much more be done in the direction of determining what the limit of solubility actually was. All steelmakers knew that over-oxidised steel produced by using slags too highly charged with iron oxide was liable to have inferior mechanical properties. It had been stated by one careful observer that if the slag, when refinement of the charge was almost complete, contained too much iron, "pigging back" with new pig iron or crude iron so as to normalise the slag would not lead to the production of the best kind of steel. As stated by Mr. Cosmo Johns, it was believed by some the difference in softness between acid and basic hearth steel was due to oxygen in the basic metal, but that was only a hypothetical conclusion.

Mr. Whiteley's valuable work had shown that when testing for oxygen in steel the drillings must be very fine and the temperature and time sufficient, otherwise the reducing agent hydrogen would not penetrate and remove the oxygen from the internal portions. He hoped Mr. Whiteley would continue his work and actually determine the true amount of oxygen in acid, basic, and other steels, and their physical properties. The suggestion that it was possible for the oxide to be concentrated locally appeared to be the case in the experiments of Le Chatelier and Bogitch and McCance.

Dr. McCance's statement regarding the carbonisation of steel when melted in vacuum, and the same steel recarburised retaining its carbon under such treatment, was certainly difficult to explain. If it originally contained 0.5 per cent. carbon, and that were removed by the oxygen in the steel itself, it would mean that the steel must have contained about 0.7 per cent. oxygen, which was far in excess of anything ever found. He was glad that Dr. McCance had been correlating temperature and absorption of oxygen in liquid steel. His observation should be useful to the steel melter. He well remembered

Professor Arnold's aired steels, and that they indicated the presence of oxide of iron near the surface. It would be of interest, however, to find whether the aired envelopes reacted with cupric reagent. Free oxides had long since been observed in steel, but it was only recently that there had been metallurgical proof of actual solid solution.

The explanation of all differences in etching effect on a polished metallic surface, generally speaking, was merely, as stated, a question of opposite electro-position. It was true cementite-ferrite, hardenite-pearlite, on different faces of the same crystal of iron, but in all cases when there was difference in chemical solubility there was difference in electro-position.

Mr. Whiteley showed that a cupric reagent was capable of detecting oxygen in solid solution, but he did not state, and he (Dr. Stead) refrained from stating, that the reagent was delicate enough to determine whether the parts that darkened contained any oxygen. The reason for the darker area just below the white border line, both in Mr. Whiteley's and his own photographs, could not be proved. He at first thought, as did Mr. Whiteley, that it was due to movement of some of the elements towards the surface, but he had tested the part of the unoxidised iron side by side with the inside of the oxidised iron and, except for carbon, there was no difference. One explanation might be that manganese in the steel just below the surface was oxidised by the penetration of SO_2 gas, which then reacted on the manganese, leaving manganese sulphide and oxides in the globular form actually found. That would render the metallic part less rich in manganese and more readily susceptible to attack by the cupric reagent.

He quite agreed that the results obtained by Le Chatelier and Bogitch had not been vitiated, but he thought the results scarcely justified the conclusion as stated that in ordinary steels as commercially manufactured it was oxygen and not phosphorus which was revealed by cupric reagent.

It was stated in his (Dr. Stead's) paper, and on several other occasions, that nearly all solid solutions and other elements were less readily attacked than the pure iron, and because a white part would not take copper that fact alone was no proof of anything except a difference of the electric positions. What he had proved was that *ceteris paribus* the white resist portions increased proportionally as the percentage of phosphorus was increased, and that several other etching methods indicated that they did contain more phosphorus than the surrounding metal. When the white portions were removed by mechanical means and analysed, the phosphorus was determined by chemical analysis, and they were found richer in phosphorus than the average of the metal.

If no other elements but iron and oxygen were present, in order to find what element it was in the resist areas they must be removed and analysed for oxygen.

In conclusion, it should be clearly understood that at present there was not sufficient experimental fact to make any general conclusions.

If the research were followed up and extended it would most certainly lead eventually to fundamental proof.

Mr. Dodo asked¹ whether free oxide could exist in steel. The answer was : it could and did, and actual analysis proved the presence of minute quantities of oxygen up to 0.05 per cent. in some very soft steels. Chemical analysis, however, did not enable it to be proved whether the oxygen was combined in free independent particles of oxide or was in solid solutions. When cold, the microscope enabled one to see the free oxide, and certain etching reagents—such as the cupric reagent—gave indication of solid solution in the cold steel. Apparently the solution was very limited and no one yet had found to what extent oxide was soluble.

The dark spots at the junctions referred to could not be separated and analysed, but it was assumed they must be similar in composition to the outer thick scale, being more or less continuous with it at the junction of the crystals. No one had actually conclusively demonstrated the degree of solubility of liquid oxide in liquid iron, although it was generally thought that the reactions during the boiling process were the result of chemical action between dissolved oxide and carbide of iron. In a recent experiment he (Dr. Stead) had produced molten electro-iron and oxide together by burning the iron in oxygen, and after running the liquid direct into water he had failed to detect by the cupric reagent any indication of dissolved iron oxide, but the microscope revealed a multitude of minute globules of free oxide. Such an experiment, of course, only indicated that there might not be sufficient oxide dissolved to make the solid solution responsive to the reagent, not that none was in solution, for, as suggested by Professor Howe, the reagent might not be able to indicate very minute amounts of that element. What the mechanical effect of dissolved oxide in iron was had not been determined with certainty. Mr. Cosmo Johns said it had been suggested that it increased the softness.

Mr. H. Dodo (London) wrote that Mr. Whiteley explained Fig. 10 of his paper as showing the appearance of the alternating layers of the original and reduced strips after etching with reagent No. 2, and that the three darker bands on which most of the copper had been deposited were the original material. If that were so, the deoxidised material appeared to be actually the more resistant of the two. The phenomena differed entirely from the results of Dr. Stead's experiments. Dr. Stead had explained that the solid solution of oxygen in iron was relatively resistant to etching by alcoholic cupric solutions, the copper being deposited more readily on pure iron than on the solid solution. He (Mr. Dodo) wished to ask Mr. Whiteley whether his specimen constituted an exception, and if so, what he imagined to be the cause. Mr. Whiteley had stated that the striking feature was the presence of the white resistance lines at the welded junctions. Was he (Mr. Dodo) to

¹ See next page.

surmise from that statement that the oxidised particles penetrated the material in some manner and so constituted the seams shown at those junctions. If that were the case, he would like Mr. Whiteley similarly to explain the cause, as if that were so, the original layers would have to be considered as consisting of pure iron, and the seams naturally would be explained with the rich oxidised regions, whereas the appearances ought actually to coincide with the theory which Dr. Stead had put forward as the results of his experiments.

Mr. H. DODO wrote that in Dr. Stead's summary it was stated that his results appeared to indicate, *inter alia*, that "when supersaturated the oxide falls out of solution, forming separate globules of free oxide," and on p. 274 it was explained that "on examining the surfaces of the fractures that passed between the grains many of them were found to be covered by fine dark spots, evidently corresponding with the globules of oxide of iron apparent in the polished section."

He had always understood that free oxide (meaning pure oxide) could not exist in iron or steel. Was he to understand from Dr. Stead's conclusion that free oxide might exist therein? He would like to ask, What were the fine dark spots with which the fractures were covered? Did they exist mechanically, and was the free oxide ascertained by chemical analysis?

From the paper he had learned the behaviour of oxygen in solid solution in iron, but he must confess he did not yet understand the precise phenomena of oxygen in molten steel or iron. What effect would it have on the quality of the material?

For instance, would the fact that electric steel was much superior in quality to converter steel be mainly accounted for by the effect of oxygen in the respective processes? If so, what was the precise behaviour of oxygen in molten steel or iron? Possibly the question was outside the range of the paper, but nevertheless he would be glad to have Dr. Stead's opinion on the point.

Professor H. LE CHATELIER, Member of Council, wrote that Mr. Whiteley's experiments confirmed on the one hand the results previously obtained by Dr. Stead regarding phosphorus, but on the other hand did not vitiate the conclusions arrived at by himself (Professor Le Chatelier) and Mr. Bogitch, that in ordinary steels as ordinarily manufactured, it was the oxygen and not the phosphorus which was revealed by etching with cupric reagent. Mr. Whiteley's experiments showed that as a matter of fact phosphorus diffused rapidly through annealing, and ceased to be revealed by the cupric reagent. In ordinary steel, on the contrary, the unequally coloured bands were not modified even by annealing for several hours. It was necessary to prolong the annealing over several days, and even weeks, before they were modified. That non-diffusibility had indeed been established by Mr. Whiteley, who had not succeeded in making the oxygen penetrate the iron by

diffusion. That could only be done by fusion. In ordinary welding only infinitely thin layers of partially oxidised iron were obtained.

Mr. WHITELEY, replying, said that the explanation advanced by Mr. Cosmo Johns of the manner in which a concentration of iron oxide might occur in those parts of the ingot last to freeze seemed very feasible. If such selective freezing occurred, an equilibrium condition existing between the oxide and carbon in the solution would almost certainly be disturbed, and the reaction between the carbon and oxygen would probably start again with the evolution of CO. As a matter of fact, an increase in the concentration of the carbon alone in the parts last to freeze, which was well known to take place, might of itself tend to bring about the formation of CO by interaction with the oxide present. It was a common observation that the extent to which the gases were evolved from the freezing ingot depended to a large degree upon the iron oxide content of the finishing slag. Given a good heat on tapping, the higher the iron content the greater the liveliness of the metal. That occurred in both basic and acid processes, but in the latter a much greater iron content was required than in the former to give the same effect. These observations strongly suggested, as Professor Howe remarked, that FeO was held in solution to some extent in molten steel even in the presence of a considerable amount of carbon. The quantity of oxygen retained in the metal would thus seem to depend on the rate at which it was removed by the carbon on the one hand, and on the other upon the rate at which it was absorbed from the slag. The latter would in turn depend upon the free iron oxide content of the slag.

He (Mr. Whiteley) was surprised to learn from Dr. McCance that a well-marked ghost-line would disappear in half an hour on heating in hydrogen, because he had found at least an hour and often more was required. Moreover, he had found it difficult to decide in experiments of that kind whether the disappearance of the line was due to deoxidation or diffusion; also, it should be remarked that the absorption of hydrogen by the metal may possibly affect its behaviour towards the reagent. It was therefore very doubtful whether proof could be obtained in that way that the ghost-lines in steel plates and other sections were due to oxygen. Nevertheless, he was inclined to agree, as a result of various experiments, that those lines were really due, in the first place, to the presence of dissolved oxide.

Dr. McCance's remarks on the decarburisation of steel by heating it in a vacuum were of much interest. He (Mr. Whiteley) had repeatedly found that when several steels were heated together in that manner some lose carbon and others absorb it,¹ but, as far as he could ascertain, that redistribution had no relation to the oxygen content of the steels. The method which Dr. McCance had used to investigate the influence of temperature and iron oxide content of the slag upon

¹ *Journal of the Iron and Steel Institute*, 1920, vol. ii, p. 155.

the amount of oxide taken up by the metal was one which appeared to be distinctly promising, and it was to be hoped that Dr. McCance would continue that piece of research.

In reply to Mr. Dodo, it was certainly the case, in experiment 5 of the paper, that more copper was deposited by the cupric reagents on the original strip than on the deoxidised material. At present he (Mr. Whiteley) had no explanation of that effect to offer, unless it was that the phosphorus content of the reduced strips had been increased slightly during the two hours' heating in hydrogen. Certain experiments he had made had suggested that iron could lose or gain some phosphorus, according to conditions, when heated in dry hydrogen, but more work was required in that direction. Mr. Dodo asked for more light on the problem of the formation of the white resist-lines. In experiment 5, at any rate, those were not due to "the penetration of oxidised particles into the material," because no such particles were present. The strips were all quite clean before they were welded in hydrogen, and therefore the resist-lines appeared to be due, in some way, to the presence of oxygen in solid solution. In experiment 4, where strips of electrolytic iron were first soaked in iron oxide, careful examination of cross-sections of those strips failed to show any resist-lines at the margins such as subsequently appeared after welding. On this point he (Mr. Whiteley) could not entirely agree with Professor Chatelier. If the cupric reagents revealed variations in the oxygen content of a steel, the whole breadth of the original strips in experiment 5 should have constituted the white resist-lines and not merely the margins. Moreover, the fact that the same resist-lines appeared in experiment 4, seemed to indicate that the electrolytic strips had dissolved a quantity of oxide; but, as stated above, the extent to which it had penetrated into the metal could not be ascertained by cupric reagents.

Iron and Steel Institute.

ROENTGEN SPECTROGRAPHIC INVESTIGATIONS OF IRON AND STEEL.

By DR. ARNE WESTGREN (GOTHENBURG, SWEDEN).

THE following Roentgen spectrographic investigations of iron and steel have been made in the Physical Institution of the University of Lund, Sweden, and were made possible by a liberal grant from the SKF Ball Bearing Company (Aktiebolaget Svenska Kullagerfabriken) of Gothenburg, Sweden.

The investigations have shown that the atoms of iron at ordinary temperature and at 800° to 830° C. are oriented in exactly the same way, which must be considered a conclusive proof of the fact that iron, contrary to the view of certain scientists, does not undergo any allotropic transformation at 768° C. The crystal lattice of austenite and of pure iron at 1000° is different from that of iron at ordinary temperature. In martensite the iron atoms are grouped in exactly the same way as in α -iron.

THE THEORY OF CRYSTAL INVESTIGATIONS ACCORDING TO DEBYE AND SCHERRER.

A complete account of the rapid development of the Roentgen spectrographic investigation methods cannot be given here. It may be sufficient to recall the fact that M. von Laue¹ was the first to show that Roentgen rays passing through a crystalline system must cause interference phenomena. Later the British investigators, W. H. and W. L. Bragg,² made use of these phenomena in developing a method of greater practical usefulness by investigating Roentgen rays reflected against crystal surfaces.

According to Bragg's method the crystal is oriented in a certain way in relation to the direction of the radiation at each experi-

¹ München. Ber., 1912, S. 303. *Jahrbuch der Radioaktivität und Elektronik*, 1914, vol. xi. p. 308.

² "X-Rays and Crystal Structure," London, 1915.

ment. Debye and Scherrer¹ and, independently, A. W. Hull,² showed that when illuminating in the same manner a sample consisting of a great many minute crystals irregularly arranged, one obtains at one exposure all the interference lines which, according to the Bragg method, are developed in a series of exposures. If a very great number of different orientations of the crystal elements of symmetry relative to the direction of light are given, at least some crystals should be so located that interference radiation will arise. If enough different crystal positions are present, all interferences possible must occur.

Debye and Scherrer made their experiments in the following way: The sample, compressed into the shape of a cylindrical rod, was placed along the axis of a cylindrical camera made from lead, the inner walls of which were covered with a photographic film. The Roentgen light fell into the camera through a narrow tube and was directed towards the centre of the cylindrical specimen.

After an exposure lasting a few hours the film, when developed, showed lines which were obviously lines of intersection between the film cylinder and conical surfaces of radiation, which have their apexes in the illuminated specimen.

The lines are symmetrically arranged round the centre of the spectrogram. By measuring the distance between two co-ordinated lines, the radius of the film cylinder being known, it is possible to find the apex angles of the interference cones.

If θ equals one-half of such an apex angle, one finds, according to Bragg:

$$d = \frac{n\lambda}{2 \sin \frac{\theta}{2}} \quad . \quad . \quad . \quad (1)$$

where d is the distance between the two consecutive atom planes in the plane series, which give rise to these interference lines, λ is the wave-length of the Roentgen light, and $n = 1, 2, 3 \dots$, according to whether the interference is of the 1st, 2nd, 3rd, or higher order.

From each Debye spectrogram a series of values for $\sin \frac{\theta}{2}$

¹ *Nachrichten der K. Ges. d. Wiss. Göttingen Math. phys. Klasse*, Feb. 27, 1915; *Phys. Zeitschr.*, 1916, vol. xvii. p. 277; 1917, vol. xviii. pp. 291, 483.

² *Physical Review* (II.), 1917, vol. ix. p. 84; 1917, vol. x. p. 661.

is obtained, from which the lattices of the crystals can be calculated. Let h_1, h_2, h_3 be the crystallographic indices of a crystal surface, *i.e.*, the inverted values of its intersections on the axis of a co-ordinated system, defined by three crystal edges, intersecting at one point; the relative lengths of the crystal axes taken as units. If the crystal belongs to the regular system, obviously all existing atom plane distances d of the lattice are comprised in the formula:

$$d^2 = \frac{a^2}{h_1^2 + h_2^2 + h_3^2}$$

where a is the side of the elementary cube. Hence

$$a^2 = \frac{n^2 \lambda^2 (h_1^2 + h_2^2 + h_3^2)}{4 \sin^2 \frac{\theta}{2}} \quad (2)$$

If the lattice be a simple cubic one, all groups of planes corresponding to these distances will, when suitably illuminated, give rise to interference radiation. If, however, the cubic lattice be built up in a more complicated way, for instance cube-centred, face-centred, or so on, certain interferences are eliminated on account of atom planes being inserted between those of the simple cube.

For cubic lattices the values of $\sin^2 \frac{\theta}{2}$ are therefore in proportion to each other as the members of a series formed by the consecutive values of $(h_1^2 + h_2^2 + h_3^2)$, where each of h_1, h_2 , and h_3 can be 0, 1, 2, 3, 4, &c. For the simple cubic lattice the $\sin^2 \frac{\theta}{2}$ values correspond with the series 1, 2, 3, 4, 5, 6, 8, 9, &c., for the cube-centred lattice 2, 4, 6, 8, 10, 12, 14, &c., and for the face-centred lattice 3, 4, 8, 11, 12, 16, 19, &c.¹ Consequently the first step in trying to interpret a Debye spectrogram should be to examine if the $\sin^2 \frac{\theta}{2}$ values, belonging to a certain wavelength, are in proportion to each other as a series of numbers, formed by three squares. If this be found to be the case, there is a high probability that the examined substance crystallises

¹ Compare with A. W. Hull, *loc. cit.*

in the cubic system. The special lattice type can then be determined with the aid of the values found missing in its $\text{Sin}^2 \frac{\theta}{2}$ series, when it is compared with the complete $(h_1^2 + h_2^2 + h_3^2)$ series, where h_1 , h_2 , and h_3 can have any integer value.

The correctness of a determination carried out in such a way can be checked by calculating from other data the volume of the elementary cube; for the mass contained within the elementary cube can be expressed in two ways, either as the product of the volume of the elementary cube and the specific weight of the substance, or in the form of the total absolute weight of the atoms forming the elementary cube. The absolute weight of an atom can be obtained in grammes by multiplying its atomic weight with $1.664 \cdot 10^{-24}$ (the absolute weight of the oxygen atom being $26.630 \cdot 10^{-24}$ grms.). If this calculation of the elementary volume leads to the same result as that obtained from the spectrogram, this obviously gives a strong support to the assumption that the spectrogram is correctly interpreted.

For crystals belonging to other systems than the regular, the interpretation of the spectrograms is considerably more complicated. In all cases, however, $4 \text{Sin}^2 \frac{\theta}{2}$ should be a homogeneous square function of h_1 , h_2 , and h_3 .¹ Hence :

$$4 \text{Sin}^2 \frac{\theta}{2} = k_{11}h_1^2 + k_{22}h_2^2 + k_{33}h_3^2 + 2k_{12}h_1h_2 + 2k_{13}h_1h_3 + 2k_{23}h_2h_3. \quad (3)$$

All lines in a spectrogram are thus arranged according to such a formula. The six constants completely characterise a unit parallelopiped, containing a so-called base group of atoms.

EXPERIMENTAL METHODS.

The Roentgen tube used in the experiments made in Lund has been exhaustively described by A. Hadding.² During the experiments the tube was run with a current of 15 to 20 milliamperes at a voltage of 40,000 volts. The anticathode consisted of iron. Around the anticathode were arranged three aluminium

¹ Debye and Scherrer, *Phys. Zeitschr.*, 1917, vol. xviii. p. 294. Compare also with C. Runge, *Phys. Zeitschr.*, 1917, vol. xviii. p. 509.

² *Zeitschr. f. Physik*, 1920, vol. iii. p. 369.

windows, through which the Roentgen radiation emerged, allowing exposure to be taken simultaneously in three cameras.

In general the cameras were of the same type as those used by Debye and Scherrer, that is, they consisted of cylindrical thick-walled lead vessels, which could be closed by a lead lid.

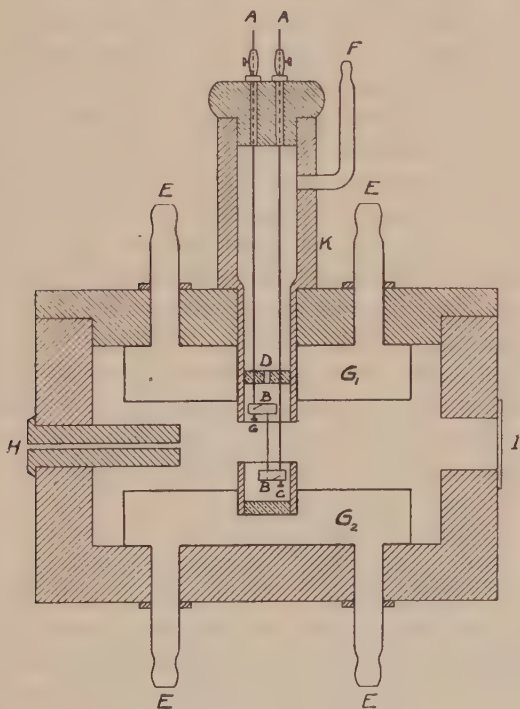


FIG. 1.

By means of a rubber band the film was fixed round a circular shoulder on this lid. Fig. 1 shows a section of a camera constructed for exposures at high temperature. A camera of the common type, such as a lead vessel with entrance tube H and outlet I, was provided with special devices for cooling the camera, for heating the specimen, and for introducing an inert gas so as to prevent oxidation of the specimen. G_1 is an annular and G_2 a cylindrical brass vessel, which are cooled by running water through the inlet pipes E. Through a hole in the camera lid

and the annular vessel a brass tube fitting accurately into the hole can be inserted. The upper part of this tube is heavier and rests against the lid by means of a flange. In the lower part of the tube an annular portion is cut away, only two brass bands (not shown on the figure) being left. These hold the lowest part of the tube, which is inserted into a cylindrical recess in G_2 . Through a fibre plug, closing the top opening of the tube, are drawn two copper wires, which pass through holes in a fibre plate D and end in two copper blocks E, through which are drilled two vertical holes (dotted on the figure) and also two fine horizontal holes. By means of the screws C a 0.2 millimetre iron wire (Merck, Darmstadt, 99.9 per cent. Fe) is clamped and then twisted round the blocks and drawn through the vertical holes. The copper wires are kept in suitable positions by the screws at A so as to stretch the iron wire between the blocks B and place its centre in front of the opening of the entrance tube. In arranging the camera for exposure the tube K is turned to such a position that the longer of the two copper wires A is placed outside the Roentgen beam, so that only the iron wire is exposed to the Roentgen radiation. Seen from the iron wire, however, narrow portions of the film are shadowed by the copper wire and by the narrow brass bands which join the upper and lower parts of the tube. By suitably arranging the copper wire in relation to these bands its shadow can be made to coincide with one of the other. Furthermore, the two shadowed parts can be placed unsymmetrically on the film, so that the whole spectrogram may be still well defined. On to the front of the outlet a cover-glass is cemented as a window, through which the wire can be observed during the experiments. Through the tube F during the experiments from hydrogen sulphide carefully purified dry hydrogen gas is injected under some pressure, whereby the camera is kept permanently filled with the gas.

The film, enclosed in an envelope of black paper to protect it against ordinary light, was fastened by a rubber band around the cooling cylinder G_1 . In order to allow the undeflected light to pass undisturbed out of the camera, and also to permit observations of the wire specimen, a circular hole was punched in the middle of the film and the envelope, the film being so placed that this hole coincided with the window.

The wires A were connected with the poles of a storage battery. By means of an adjustable resistance coupled in the circuit the current could be so regulated that the specimen attains the desired temperature. This temperature was approximately determined by means of an optical pyrometer of the Holborn-Kurlbaum type. An exact temperature determination was not possible in this way, since evidently the glowing wire in the camera does not radiate as an absolutely black body. By the optical pyrometer, however, a lower limit for the actual temperature is determined, which was found by special checking experiments to be not more than 30° too low.

Debye and Scherrer have pointed out the necessity for pulverising very finely the substance to be investigated according to their methods. Accordingly, in their metal investigations filings or folded fine-drawn wires have mainly been used.¹

Since, however, most metals consist of aggregates from small crystals, it appeared probable to the author that continuous metal specimens ought to give as good interferences as finely divided metal. This supposition was fully confirmed by experiments. The iron and steel samples therefore were investigated in the form of cylindrically ground rods of the dimensions 10 by 2 millimetres.

CRYSTAL STRUCTURE OF IRON MODIFICATIONS.

Having worked out the new method for determining the crystal lattice of a finely divided substance, Hull tested this method on some metals; the crystal structure of iron at ordinary temperature was also determined. This lattice was found to be a cube-centred cubic one and the edge of the cube was 2.86 \AA . ($1 \text{ \AA} = 10^{-8} \text{ centimetre}$). This result was verified by some measurements on Bragg's method, made on a well-developed iron crystal containing about $3\frac{1}{2}$ per cent. silicon.

The results found by Hull with soft iron at ordinary temperature were also verified by the investigations in Lund. In the first column of Table I., under the heading r , are given the shortest distances in millimetres from the centre to the lines in a spectrogram of a 0.25 millimetre iron wire with a carbon content of

¹ Compare also A. W. Hull, *loc. cit.*

0.15 per cent. θ is half the apex angle of each radiation cone.

In the radiation emitted from an iron anticathode the so-called K_α -line predominates. Its wave length is 1.932 Å. The kind of radiation nearest in strength is K_β of the wave-length 1.754 Å. In this case only these two lines in the Roentgen spectrogram of iron have sufficient intensity to cause interference radiation. The interference lines produced by K_α should be considerably clearer than those originating from K_β . In column I. of Table I. an estimate of the intensity is given for each line.

TABLE I.—*Iron Wire, 0.25 millimetre. Carbon content, 0.15 per cent. Diameter of film cylinder, 50.0 millimetres. Time of exposure, 2 hours.*

r .	I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d .		h_1, h_2, h_3 .	Radiation.
					Obs.	Comp.		
23.1	w.	52.9	0.445	0.198	1.98	2.01	110	K_β
25.5	st.	58.4	0.488	0.238	1.98	2.01	110	K_α
33.7	w.	77.2	0.624	0.389	1.41	1.42	200	K_β
37.8	me.	86.6	0.686	0.471	1.41	1.42	200	K_α
43.2	w.	99.0	0.760	0.578	1.16	1.16	211	K_β
49.4	st.	113.2	0.835	0.697	1.16	1.16	211	K_α
53.0	v.w.	121.5	0.872	0.760	1.01	1.00	110 ($n=2$)	K_β
64.2	st.	147.1	0.959	0.920	1.01	1.00	110 ($n=2$)	K_α

St. indicates a strong line, me. a line of medium strength (*i.e.* somewhat less prominent), w. a weak line, and v.w. a hardly visible one. As seen from Table I. weak and strong lines alternate. The weak lines may originate from K_β , the strong lines being caused by K_α . If this be the case, according to Bragg's formula

$$d = \frac{n\lambda}{2 \sin \frac{\theta}{2}}$$

the ratio between the $\sin \frac{\theta}{2}$ -values for co-ordinated lines caused by K_β and K_α should equal the ratio between the wave-lengths of these kinds of radiation, *i.e.* equal to $\frac{1.754}{1.932} = 0.908$. The

quotients of the $\text{Sin} \frac{\theta}{2}$ -values of two consecutive weak and strong lines in the table are :

$$\frac{0.445}{0.488} = 0.912; \quad \frac{0.624}{0.686} = 0.909; \quad \frac{0.760}{0.836} = 0.910; \quad \frac{0.872}{0.959} = 0.909.$$

Hence it is proved that each line in the spectrogram produced by K_{α} is accompanied by a weaker line produced by K_{β} .

The $\text{Sin}^2 \frac{\theta}{2}$ -values for K_{α} are found to be in the proportion 1.02, 2.00, 2.99, 3.95, and the corresponding values for K_{β} are 1.03, 2.02, 3.00, 3.96. Accordingly the crystals of the iron wire should belong to the cubic system. From these figures alone, however, it is not possible to decide whether we are dealing with a simple cubic lattice or a cube-centred one. As already mentioned, Hull, who used a Roentgen light of short wave-length and consequently obtained a greater number of interference lines, found that the lattice in question is cube-centred. On the basis of the figures in Table I. we arrive at the same conclusion. If the unit cubes of the iron crystals are simply cubic, they must contain one atom, but if they are cube-centred, two atoms.¹

In the manner described above the edge of the cube can be calculated from the specific weight and the atomic weight of iron under the two conditions above-mentioned. The specific weight of iron is 7.86 and the atomic weight 55.8. For the simple cube we have

$$d_s^3 = \frac{55.8 \cdot 1.664 \cdot 10^{-24}}{7.86}$$

which gives $d_s = 2.29 \text{ \AA.}$, and for the cube-centred one

$$d_c^3 = \frac{2 \cdot 55.8 \cdot 1.664 \cdot 10^{-24}}{7.86}$$

which gives $d_c = 2.87 \text{ \AA.}$

From the figures in Table I. the medium value for the edge of the unit cube is found to be $d = 2.83 \text{ \AA.}$ Thus from the spectrogram of the iron wire a verification has been obtained of the result

¹ In the cube-centred cube there are eight corner atoms, one-eighth of each belonging to the cube, and one atom in the centre of the cube, which make a total of two atoms. In the simple cube there are only eight corner atoms, which together equal one atom only.

found by Hull, namely, that pure iron at ordinary temperature has a cube-centred cubic lattice.

In starting this investigation of an ordinary iron wire, the original intention was not only to repeat Hull's determination but also to make possible a correction of spectrograms obtained with other samples. These had been obtained from cylindrically ground rods or from compressed powder enclosed in thin-walled cylinders of film of gelatine of a similar shape. On account of the very strong absorption in these specimens the interference radiation comes from their surface layers only. The effect of this circumstance, combined with a weak divergence in the incoming Roentgen beam, is that the lines on the film are somewhat displaced as compared with the ideal spectrogram which would result if the specimen were an infinitely thin wire accurately placed along the axis of the camera cylinder. By comparing the spectrogram obtained from the above-mentioned 0.25 millimetre wire and a spectrogram from a 2-millimetre iron cylinder in the same camera, the magnitude of this displacement in the different parts of the film is found, and the spectrograms of the heavier specimens are corrected accordingly. Unfortunately the iron wire was not exactly in the middle of the camera, as is also indicated by a slight systematic variation in the figures of the table. The specimens, however, in all experiments in the same camera, having been placed in exactly the same way, the error thus caused can be eliminated in all spectrograms by comparison with a spectrogram calculated theoretically for pure α -iron. The r -values measured have also to be somewhat corrected for shrinkage of the film during development and fixation. The total from these corrections amounts to 1.4 millimetre for $r = 20 - 25$ millimetres, to 1.5 millimetre for $r = 25 - 50$ millimetres, whereas for higher r -values it sinks successively to 0.8 millimetre.

The next step is to examine iron in its γ -state. This is easiest done on austenitic steel, in which the γ -iron, by quenching from high temperature, is undercooled so as to be practically stable at ordinary temperature. Spectrograms were taken on two such steels—a nickel steel (nickel, 25.2 per cent.; carbon, 0.24 per cent.; manganese, 0.50 per cent.; silicon, 0.10 per cent.; phosphorus, 0.047; and sulphur, 0.010 per cent.); and a man-

ganese steel (manganese, 12.1 per cent. ; carbon, 1.34 per cent. ; silicon, 0.52 per cent. ; and phosphorus, 0.10 per cent.). Both were quenched in water from about 1000°. The specimens used were small, cylindrically ground rods of 10 millimetres length and 2 millimetres diameter. Extremely clear films were obtained. The results are given in Tables II. and III.

TABLE II.—*Nickel Steel (nickel, 25 per cent. : carbon, 0.24 per cent.). Quenched from 1000° in water. Diameter of film cylinder, 50.0 millimetres. Time of exposure, 45 minutes.*

r.		I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d.		$h_1, h_2, h_3.$	Radiation.
Meas.	Corr.					Obs.	Comp.		
23.4	22.1	w.	50.4	0.425	0.181	2.06	2.07	111	K_β
25.8	24.3	st.	55.7	0.467	0.218	2.07	2.07	111	K_α
27.1	25.6	v.w.	58.7	0.490	0.240	1.79	1.79	200	K_β
30.0	28.5	st.	65.3	0.540	0.292	1.79	1.79	200	K_α
39.7	38.2	v.w.	87.5	0.690	0.476	1.27	1.27	220	K_β
44.8	43.3	st.	99.2	0.762	0.581	1.27	1.27	220	K_α
48.6	47.1	w.	107.9	0.808	0.653	1.09	1.08	311	K_β
51.8	50.6	v.w.	116.0	0.848	0.719	1.03	1.03	111 (n=2)	K_β
56.5	55.5	st.	127.1	0.896	0.803	1.08	1.08	311	K_α
61.3	60.5	st.	138.7	0.936	0.876	1.03	1.03	111 (n=2)	K_α

TABLE III.—*Manganese Steel (manganese, 12 per cent. ; carbon, 1.34 per cent.). Quenched from 1000° in water. Diameter of film cylinder, 50.0 millimetres. Time of exposure, 45 minutes.*

r.		I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d.		$h_1, h_2, h_3.$	Radiation.
Meas.	Corr.					Obs.	Comp.		
23.2	21.8	w.	50.0	0.422	0.178	2.08	2.09	111	K_β
25.6	24.1	st.	55.2	0.463	0.214	2.09	2.09	111	K_α
26.6	25.1	v.w.	57.5	0.480	0.230	1.83	1.80	200	K_β
29.8	28.3	st.	64.9	0.537	0.288	1.80	1.80	200	K_α
39.2	37.7	v.w.	86.4	0.684	0.468	1.28	1.28	220	K_β
44.2	42.7	st.	97.9	0.753	0.567	1.28	1.28	220	K_α
47.8	46.3	v.w.	106.1	0.799	0.638	1.10	1.09	311	K_β
51.0	49.7	v.w.	116.9	0.852	0.726	1.03	1.04	111 (n=2)	K_β
55.5	54.5	st.	124.9	0.887	0.787	1.09	1.09	311	K_α
59.8	58.9	st.	135.0	0.924	0.854	1.04	1.04	111 (n=2)	K_α

In the spectrograms of these austenitic steels there are likewise found as many lines originating from the K_β as from the K_α radiation. The K_α lines of the nickel steel $\text{Sin}^2 \frac{\theta}{2}$ are in proportion to each other as 3.00, 4.02, 8.00, 11.05, 12.04, and the K_β lines as 3.00, 3.98, 7.89, 10.82, 11.92. The corresponding series for the manganese steel are 3.00, 4.04, 7.95, 11.03, 11.97, and 3.00, 3.88, 7.89, 10.76, 12.24. These numbers agree very closely with the series 3, 4, 8, 11, 12. Consequently the austenitic steels should have a face-centred cubic lattice. The average value of the edge of the unit cube is, according to Tables II. and III., 3.58 Å. for the nickel steel and 3.61 Å. for the manganese steel.

The number of atoms of the face-centred cube is four.¹ Whether this number is in accordance with the values found for the unit volumes of the lattices is hard to decide for the manganese steel, since the high carbon content of this steel gives rise to difficulties in calculating the weights of the atoms which form the lattice. For the nickel steel, however, with its low carbon content, such a calculation ought to be possible, as the metal atoms of this steel undoubtedly make up the building stones of its lattice, so that an average atomic weight of 56.6 may be assumed. The specific weight of the steel was found to be 8.13. By the use of the value found above for the edge of the unit cube the number of atoms per cube must be—

$$\frac{8.13 \cdot (3.58)^3 \cdot 10^{-24}}{56.6 \cdot 1.664 \cdot 10^{-24}} = 4.09.$$

This therefore proves that the austenitic crystals have face-centred cubic lattices.

If it be sought to calculate the atom number per unit cube in a similar way for the manganese steel, it may be assumed either that all atoms in the steel are arranged in the face-centred cubic lattice, or that only the metal atoms make up this lattice, the carbon atoms being arranged in a lattice of another type inserted into the former. This approaches the yet unsolved question of the lattice types of mixed crystals of solid solutions.²

¹ Eight corner atoms and six side atoms, i.e. eight-eighths of an atom and six half atoms—total four.

² Compare with L. Vegard and H. Schjelderup, *Phys. Zeitschr.*, 1917, vol. xviii. p. 93.

The average atomic weight of all the atoms in the steel is 52.7 and that of the metal atoms 55.6. The specific weight of the steel is 7.83. The number of atoms per unit volume is, on the first assumption,

$$\frac{7.83 \cdot (3.61)^3 \cdot 10^{-24}}{52.1 \cdot 1.664 \cdot 10^{-24}} = 4.24,$$

and on the second assumption

$$\frac{7.83 \cdot (3.61)^3 \cdot 10^{-24}}{55.6 \cdot 1.664 \cdot 10^{-24}} = 3.97.$$

From this it appears plausible that the latter of the two assumptions comes nearest to the truth, namely, that the carbon atoms

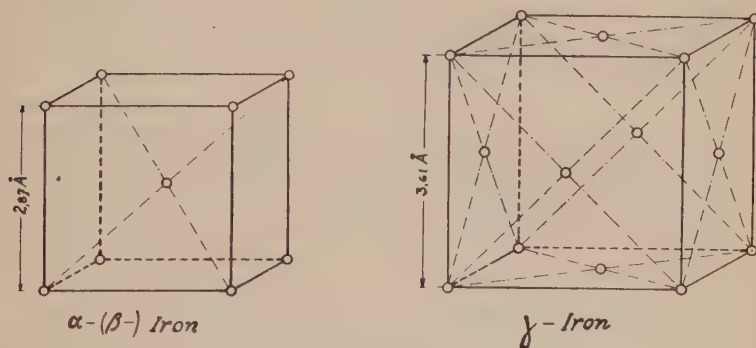


FIG. 2.

do not enter in the lattice of these atoms in the same way as do the iron and manganese atoms, but must be arranged according to some other principle. The atom groups of pure iron at ordinary temperature (α -iron) and of the austenitic steels (i.e. γ -iron) are seen from the unit cubes in Fig. 2.

From this first investigation of ordinary iron at room temperature and of austenitic steels it can be concluded that α -iron and undercooled γ -iron have different crystal structures.

In order to determine the lattices of β -iron and of γ -iron in a stable state, that is, above the calescence point, exposures were made at 800° to 830° and at about 1000° in the camera described above, constructed for experiments at high temperature. The specimen, a fine iron wire, containing 99.9 per cent. iron, should have a β -iron interval of 768° to 880°. In taking

the spectrogram of β -iron the temperature therefore was so regulated that the optical pyrometer showed 800° . The actual temperature was consequently somewhat higher, but did not exceed 830° . Since the interference radiation has to penetrate the paper envelope covering the film, its action on the film is somewhat weakened. In order to compensate for this effect the time of exposure must be longer than in the other experiments. For β -iron a spectrogram with very clear continuous lines was obtained. The film taken at 1000° shows, however, only remote black spots. Obviously the crystals at this high temperature had grown so large that only a few individual crystals were in a position suitable for interference radiation. These points, however, are sufficient for constructing a line spectrogram. The results of experiments at higher temperature are given in Tables IV. and V.¹

TABLE IV.— β -Iron. Iron Wire, 0.2 millimetre (99.9 per cent. Fe). Temperature 800° to 830° . Diameter of film cylinder, 55.0 millimetres. Time of exposure, $2\frac{1}{2}$ hours.

r .	I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d .		h_1, h_2, h_3 .	Radiation.
					Obs.	Comp.		
24.0	w.	50.0	0.423	0.179	2.07	2.07	110	K_β
26.5	st.	55.2	0.464	0.215	2.08	2.07	110	K_α
39.9	"	83.1	0.663	0.440	1.46	1.46	200	K_α
52.4	"	109.2	0.815	0.664	1.19	1.19	211	K_α
67.5	"	140.6	0.942	0.888	1.03	1.03	110 ($n=2$)	K_α

As seen from these tables, the so-called β -iron has the same lattice as α -iron. At 1000° , that is, in the γ -iron interval, the iron crystals, as might be expected, have the same structure as in the austenitic steels. The edge of the unit cube, according to Table IV., for iron at 800° to 830° , is 2.92 \AA. , which is in close

¹ Except the lines included in Table IV. in the spectrogram two extremely weak lines also appear within and in the neighbourhood of one of the K_β lines. Undoubtedly these lines were caused by the fact that the strongest interference radiation in the opposite half of the spectrogram (corresponding to $r = 26.5$ millimetres) has met the edge of one of the brass bands, so that a weak interference radiation from these brass bands results.

agreement with the theoretically calculated value 2.90 \AA . (assuming an average coefficient of expansion for iron of $15 \cdot 10^{-6}$). From the d values in Table V. we find the edge of the unit cube of

TABLE V.— γ -Iron. Iron Wire, 0.2 millimetre (99.9 per cent. Fe). Temperature about 1000° . Diameter of film cylinder, 55.0 millimetres. Time of exposure, 2 hours.

r .	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d .		h_1, h_2, h_3	Radiation.
				Obs.	Comp.		
24.0	50.0	0.423	0.179	2.07	2.08	111	K_β
26.7	55.6	0.467	0.218	2.07	2.08	111	K_α
31.6	65.8	0.542	0.294	1.78	1.80	200	K_α
41.5	86.5	0.686	0.471	1.28	1.27	220	K_β
47.0	97.9	0.754	0.569	1.28	1.27	220	K_α
59.5	124.0	0.883	0.780	1.09	1.08	311	K_α
63.8	132.9	0.917	0.841	1.05	1.04	111 ($n=2$)	K_α

γ -iron (1000°) to be 3.60 \AA ., which well agrees with the theoretical value of 3.65 \AA .

These spectrograms, taken at higher temperatures, prove therefore that a fundamental difference exists between the apparent transformation point of iron A2 and the critical point A3. No difference has been found in the structure of iron below and above A2. At A3, however, the atoms of iron are completely rearranged and the iron passes from one crystal class into another. Consequently, the difference between iron of the α - and β -states is not of the same kind as that between the α - and γ -states.

The so-called β iron problem is evidently, however, not completely solved. The spontaneous change in energy of iron at 768° in heating or cooling still remains to be explained. It is, of course, conceivable that the known interpretation by C. Benedicks¹ of the transformation may finally prove to be correct, that is that the transition from the γ - to the α -state takes place continuously. Thus the lattice transformation in cooling would not be complete at the transformation point A3, but the face-centred lattice

¹ *Journal of the Iron and Steel Institute*, 1912, No. II. p. 242.

would still exist in certain points of the system and not transform until at low temperature, the last remainders recrystallising at A2. The possibility of such a process cannot be dismissed, particularly in view of the fact that Hull¹ found certain nickel preparations to consist of a mixture of crystals with cube-centred and face-centred lattices. It is possible that the Roentgen spectrographic methods, combined with accurate temperature determinations of the illuminated iron specimen, will give further information as to the mechanism of the α - and γ -transformation.

Finally, there remains the much-debated question whether the β -iron should be considered as a special allotropic modification or not. Evidently this must depend upon how the term allotropy is defined. In the very animated discussions raised by this question during recent years many different suggestions have been made. Some of these, representative of different opinions, may be quoted here. Sauveur² considers an allotropic transformation to correspond with a spontaneous change in energy in a body at a certain temperature. According to Burgess and Crowe³ and to Honda⁴ allotropy is synonymous with polymorphy, that is, two allotropic forms of the same substance have different crystal structures. This definition is opposed by Benedicks,⁵ who holds that neither the crystal structure nor any other arbitrary properties of a substance can decide the question whether it has different allotropic forms or not. Benedicks falls back on Gibb's definition of the term allotropic transformation, and states that an allotropic transformation point is defined by two phases of the same substance being in equilibrium with each other at a certain temperature.

This definition appears to the author rather too abstract. The term allotropy was evidently coined to cover a whole group of phenomena. It should therefore be so defined that it is always possible to decide in concrete cases whether there is allotropy or not. Whether a two-phased equilibrium system exists at a certain temperature or not can only be decided by an investigation of the properties of the phases, and the fact that two phases

¹ *Phys. Review*, II., 1917, vol. x. p. 691.

² *Journal of the Iron and Steel Institute*, 1913, No. II. p. 171.

³ *Scientific Papers, Bureau of Standards*, 1914, No. 212.

⁴ *Journal of the Iron and Steel Institute*, 1915, No. I. p. 199; 1919, No. I. p. 457.

⁵ *Ibid.*, 1914, No. I. p. 435.

really do exist cannot be established until differences between these phases have been ascertained. Theoretically the two phases must evidently differ in most respects, but for practical reasons it would be an advantage if a certain property could be regarded as decisive of allotropy.

The fact that to many physicists the crystal shape is of fundamental importance in this respect cannot, obviously, be a matter of chance, but arises from the very plausible assumption that a spontaneous change in the properties of a substance at a certain temperature is due to a rearrangement of its atoms and consequently to a change in the crystal structure. A rearrangement of the atoms in a crystal could hardly be imagined as taking place without a simultaneous change in energy. Sauveur's definition of allotropy, however, is not practical, since there is always a possibility that the changes in energy may be too small to be experimentally proved.

For reasons given above the author does not hesitate to agree with the opinion that allotropy for crystalline substances is equal to polymorphy. Following this definition the conclusion he draws from his Roentgen spectrographic investigation of iron at 800° is that an independent β -modification does not exist.

CRYSTAL STRUCTURE OF STEEL IN HARDENED STATE.

In what precedes it has been shown how the Roentgen spectrographic investigations have confirmed the view that quenched austenitic steel has γ -iron structure. In order to ascertain the structure of the iron crystals in the technically more important and interesting martensite, spectrograms were taken of the quenched nickel and manganese steel specimens mentioned above, after these had been cooled in liquid air. The manganese steel still gave a γ -iron spectrogram. The spectrogram of nickel steel, however, was materially changed. Its lines were unsharp and diffuse, indicating that the steel had become extremely finely crystalline in structure.

As seen from Table VI., where the r -values measured are given, the γ -iron lines still exist, although weakened and somewhat displaced outwards from the centre of the spectrogram. In addition, however, a number of new lines appear, several of which

are prominent. The inmost line, which is 21 millimetres from the centre of the spectrogram, does not belong to any of the ordinary α - and γ -iron interferences, and its origin is still unexplained. Neither has this line been found in the spectrograms which the author later has obtained of pure cementite, so it is certainly not caused by Fe_3C separated in the steel.

If the edges of the unit cubes for the lattices of this steel be calculated, the values 2.81 Å. for the cube-centred lattice

TABLE VI.—*Nickel Steel (nickel, 25 per cent.; carbon, 0.24 per cent.). Quenched from 1000° in water. Cooled in liquid air. Diameter of film cylinder, 49.9 millimetres. Time of exposure, 2 hours.*

$r.$		I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	$d.$		$h_1, h_2, h_3.$	Radiation.	Iron Modification.
Meas.	Corr.					Obs.	Comp.			
21.0	19.5	v.w.	44.8	0.381	0.145	2.54	...	...	\text{K_α	...
24.5	23.0	w.	52.8	0.444	0.197	1.98	1.99	110, 111	K_β	$\alpha(\gamma)$
27.0	25.5	st.	58.5	0.490	0.240	1.98	1.99	110, 111	K_α	$\alpha(\gamma)$
30.7	29.3	w.	67.3	0.553	0.306	1.75	1.77	200	K_α	γ
39.5	39.2	w.	90.0	0.707	0.500	1.37	1.40	200	K_α	α
45.5	44.2	w.	101.5	0.774	0.599	1.25	1.25	220	K_α	γ
50.5	49.3	st.	113.2	0.835	0.677	1.16	1.14	211	K_α	α
54.1	53.0	v.w.	121.7	0.873	0.762	1.00	1.00	110 ($n=2$)	K_β	α
57.2	56.3	st.	129.3	0.903	0.815	1.07	1.07	311	K_α	γ
61.7	60.9	w.	139.9	0.939	0.882	1.03	1.02	111 ($n=2$)	K_α	γ
64.5	63.7	st.	146.3	0.957	0.916	1.01	1.00	110 ($n=2$)	K_α	α

and 3.54 Å. for the face-centred one are found. These values are in fact somewhat lower than the values theoretically calculated for pure α - and γ -iron. The discrepancy, which may be due to experimental errors (faulty centering of the specimens in the camera, divergence of the incident Roentgen beam, and so on), is, however, not sufficiently large to vitiate the above conclusion that this nickel steel consists of a mixture of α - and γ -iron.

Photomicrographs of the two steels cooled in liquid air are given in Figs. 3 and 4 (Plate XIX.). As seen from these, the manganese steel still consists of austenite, whereas the nickel steel shows coarse martensite needles mixed with austenite.



FIG. 3.

12 % Mn. ; 1.37 % C.
Quenched in water at 1000° C.
Cooled in liquid air.

Magnified 400 diameters.

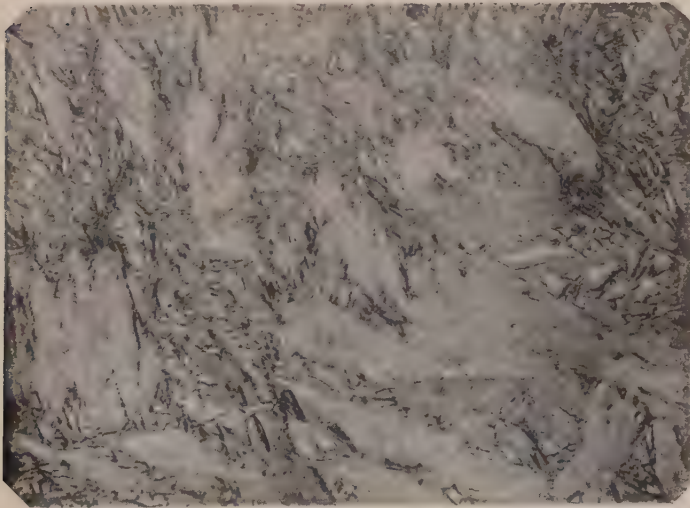


FIG. 4.

25 % Ni. ; 0.24 % C.
Quenched in water at 1000° C.
Cooled in liquid air.

Magnified 400 diameters.

To face p. 320.

From the nickel steel spectrogram mentioned above it can be concluded that the martensite formed by cooling the austenite probably contains α -iron. In order to ascertain this, hardened carbon steels were also examined. It was to be expected that at the same time information could be obtained as to the crystal structure of cementite. Spectrograms of annealed steels containing about 1.25 per cent. carbon showed, however, only the lines of α -iron. Although the cementite present in this steel amounts to about 18 per cent., no Fe_3C lines appeared on the films. The investigation therefore was limited to the determination of the grouping of the iron atoms only in a hardened carbon steel. Table VII. gives the result obtained.

TABLE VII.—Steel SKF 1 (carbon, 1.25 per cent.). Quenched from 760° in water. Diameter of film cylinder, 50.3 millimetres. Time of exposure, 50 minutes.

r.		I.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d.		$h_1, h_2, h_3.$	Radiation.
Meas.	Corr.					Obs.	Comp.		
23.3	22.2	w.	51.3	0.432	0.187	2.03	2.04	110.	K_β
25.8	24.9	st.	56.7	0.474	0.225	2.04	2.04	110	K_α
33.8	32.9	v.w.	75.0	0.609	0.371	1.44	1.44	200	K_β
37.8	36.9	me.	84.1	0.669	0.448	1.45	1.44	200	K_α
43.4	42.5	v.w.	96.8	0.748	0.560	1.18	1.17	211	K_β
49.4	48.5	st.	110.5	0.822	0.676	1.17	1.17	211	K_α
64.5	63.5	st.	145.0	0.954	0.910	1.01	1.02	110 ($n=2$)	K_α

In this spectrogram, likewise, the lines were somewhat diffuse, indicating that the steel in hardening had become very finely crystallised. From the d -values observed in Table VII. it is seen that the edge of the unit cube is 2.88 Å.

Finally a hardened high-speed steel was also examined. Many lines were seen in its spectrogram. Among these were found all the strongest α -iron lines, but no interference lines originating from γ -iron. Table VIII. gives a list of all the lines of the high-speed steel. The edge of the unit cube in the α -iron lattice was found to be 2.86 Å. The other lines of the spectrogram undoubtedly originate from the other phase in the steel,

that is, from the carbide. Since this, however, can hardly consist of a single chemical substance, but is probably a mixture, and furthermore since its series of lines in the spectrogram of the high-speed steel is not complete, it did not seem worth while to attempt to determine its lattice on the basis of the figures given in Table VIII. A separate investigation is now being started dealing with the question of the carbides in the tungsten steel. The results will be reported later on.

TABLE VIII.—*High-speed Steel "Dannemora Brilliant AX." Quenched from 1275° in oil. Diameter of film cylinder, 50.0 millimetres. Time of exposure, 1½ hours.*

τ .		L.	θ	$\sin \frac{\theta}{2}$	$\sin^2 \frac{\theta}{2}$	d .		h_1, h_2, h_3 .	Radiation.	Phase.
Meas.	Corr.					Obs.	Comp.			
19.5	18.1	v.w.	41.5	0.354	0.125	...	...	...	...	Carbide
21.5	20.1	v.w.	46	0.391	0.153	...	...	...	...	"
22.9	21.4	v.w.	49.0	0.415	0.172	...	...	...	...	"
24.0	22.5	w.	51.6	0.436	0.190	2.01	2.02	110	K_β	α -iron
25.3	23.8	w.	54.6	0.459	0.211	...	...	...	...	Carbide
26.5	25.0	st.	57.3	0.480	0.230	2.02	2.02	110	K_α	α -iron
27.6	26.1	w.	59.8	0.498	0.248	...	...	...	...	Carbide
34.1	32.6	v.w.	74.7	0.607	0.368	1.44	1.43	200	K_β	α -iron
35.3	33.8	w.	77.5	0.626	0.392	...	...	...	...	Carbide
38.4	36.9	st.	84.6	0.673	0.453	1.44	1.43	200	K_α	α -iron
41.7	40.2	me.	92.1	0.720	0.518	...	...	...	...	Carbide
43.2	41.7	me.	95.6	0.741	0.549	...	...	...	...	"
44.5	43.0	v.w.	98.6	0.758	0.575	...	...	...	...	"
49.8	48.4	st.	118.9	0.824	0.679	1.17	1.17	211	K_α	α -iron
52.0	50.7	v.w.	116.2	0.849	0.721	...	...	...	...	Carbide
53.8	52.5	st.	120.3	0.867	0.752	...	...	...	...	"
56.2	55.0	w.	126.1	0.891	0.797	...	...	...	...	"
57.8	56.8	me.	130.2	0.907	0.823	...	...	...	...	"
63.5	62.7	st.	143.7	0.951	0.904	1.01	1.01	110 ($n=1$)	K_α	α -iron

A spectrogram taken of hardened high-speed steel of ordinary composition, tempered at 575°, was identical with that one recorded in Table VIII.

The Roentgen spectrographic investigations of martensite showed that its iron atoms are oriented in exactly the same

way as in ferrite. The iron of martensite is consequently identical with that of ferrite, and the difference in hardness between these two structural constituents is not due to the iron but to the carbon present in the martensite. The great question is, therefore, how are the carbon atoms in the martensite arranged? The spectrograms so far obtained yield, unfortunately, no information on this point. It might be, however, that improved methods will yield such information in the future.

One possibility seems to be that amicroscopic¹ cementite crystals form in the moment of martensite formation, and remain distributed in the crystal mass of the ferrite. On tempering these crystals grow to larger crystals, thus forming, together with the α -iron, the series troostite, sorbite, and pearlite, with increased tempering. This hypothesis consequently involves an expansion of the known colloid-chemical explanation of tempering phenomena of Benedicks.² Tempering of hardened steel would thus be nearly analogous with the processes which occur on heating the classical substance of ultramicroscopic investigation, gold ruby glass. Siedentopf and Zsigmondy,³ by means of their ultramicroscope, found the appearance of the beautiful red colour on heating such a glass to be due to colloid gold being precipitated in the glass mass, the gold crystals on increasing temperature growing in size. Zsigmondy⁴ interprets this growth as due to small gold crystals forming centres of precipitation in the gold solution which is oversaturated by under-cooling. Possibly the precipitation of cementite from martensite occurs in a similar way, but it seems more probable that the cementite already present at the moment of martensite formation is precipitated in an extremely finely divided form, and that the growth of the cementite grains on tempering involves a coagulation, that is, an accretion of amicroscopic cementite crystals to larger units.

Whether one or the other of these assumptions be valid, that is whether the martensite is a solid solution of carbon in ferrite or consists of cementite colloidally precipitated in ferrite, the hardness of the steel can be explained. It is evident that the

¹ *Amicroscopic*, that is, particles too small to be detected even by ultramicroscopic methods.

² *Kolloid Zeitschrift*, 1910, vol. vii. p. 290.

³ Drudes, *Annalen d. Phys.*, (4), 1903, vol. x. p. 1.

⁴ *Zur Erkenntnis der Kolloide*, Jena, 1905, pp. 128-135.

crystal lattice cannot have the same strength in a pure state and when foreign atoms or complexes of atoms are inserted into it. If the orientation of the carbon atoms in the martensite α -iron lattice were known, it should be possible to carry out a theoretical calculation of their influence on the resistance of the lattice against exterior forces. In this connection the author would refer to the very important work on the strengths of crystal lattices made by M. Born and A. Landé¹ during the last years.

Assuming that the forces holding the atoms in a lattice are electric in nature and obey very simple laws, these physicists have been able to calculate the compressibility of alkaline halogenoid crystals and have thus theoretically arrived at values which are in good agreement with those experimentally determined. In this field modern crystal investigation methods afford great promises in metallographic research. Having once found the lattices of metals and metal alloys and the laws for the forces that govern the lattice equilibrium it ought to be possible theoretically to determine the strength of the systems. In this way perhaps problems dealing with the strength of materials, which have hitherto been soluble only by empiric methods, may be open to theoretic treatment and become based on a rational scientific foundation.

SUMMARY.

The results obtained from the Roentgen spectrographic investigations related may be summed up as follows :

1. Hull's result that iron at ordinary temperature (α -iron) has a cube-centred cubic lattice structure is verified.
2. At 800° to 830° C., that is, within the so-called β -iron interval, the iron atoms are oriented in exactly the same way as in α -iron. Allotropy being in the author's opinion equal to polymorphy for solid crystalline bodies, this means that β -iron cannot be considered as a separate modification of iron.
3. In austenite and in iron at 1000° the iron crystals have face-centred cubic lattices. This is consequently characteristic

¹ *Verh. d. Deutsch. Phys. Ges.*, 1918, vol. xx. p. 210.

of γ -iron, and a fundamental difference in crystallographic respect is found between α - and γ -iron.

4. In martensite iron is in the form of its α -modification. This is the case also in high-speed steel of ordinary composition, hardened at 1275°.

This paper is only a brief report on the first results obtained by the application of Roentgen spectrographic methods to metallographic problems. The investigations are being continued and will be extended to include complex phases in steel and other alloys. Spectrograms of cementite recently obtained show that the crystal structure of cementite is related to that of γ -iron, a fact that explains the mutual solubility of these phases. A few spectrograms of tungsten carbides have also been taken. For these investigations a separate report will shortly be published.

As already mentioned all the Roentgen experiments were made at the Physical Institution of the Lund University. The fact that the investigations could be carried out without considerable difficulties, with the result that very clear spectrograms were obtained after comparatively short time of exposure, should be attributed to the energy with which the experimental developments of the Debye method have been worked out in the Institution. The author is indebted to Professor M. Siegbahn for kindly putting the Roentgen apparatus at his disposal. He desires also especially to express his thanks to Mr. Axel E. Lindh for his most competent assistance in taking the spectrograms. Finally he would like to put on record his indebtedness to the Management of the SKF Ball Bearing Company, who have enabled him to carry out these experiments in the course of his work at their Laboratory and have also contributed the means necessary for the work.

DISCUSSION.

Sir WILLIAM BRAGG (London) said he had spent some time in trying to investigate the crystalline nature of materials by X-ray methods, and Dr. Westgren described experiments in which X-ray methods were applied for the first time to certain very important metallurgical questions.

The examination of α , β , and γ iron by Dr. Westgren had shown that in the first two modifications the fundamental lattice was that of the centred cube, that was to say, that the lattice was built on a cubic pattern in which each element might be supposed to consist of one atom at each corner and one in the centre of the cube. He claimed to have shown that the architecture of the γ -iron was different and that the lattice was now face-centred; in other words, that the atoms were close packed like a pile of shot. The unit of pattern might still be taken as a cube, but there was now one atom in each corner of the unit and one atom in the centre of each face. The proposition relating to α -iron had already been established by Hull,¹ and the two determinations agreed very closely. Hull found that the length of the cube side was 2.86 Ångström units,² agreeing with Dr. Westgren's determination as 2.87. That agreement, however, was to be expected, because as soon as the X-rays had determined the structure of the lattice the calculation of the length of the cube side depended only on the knowledge of the specific gravity of iron and the weight of the iron atom. A further simple calculation showed that the distance between the centres of two iron atoms was 2.47 Å.U. Hull had not found in the paper referred to any difference between α and γ iron, but Dr. Westgren's experiments appeared to establish the effects that he now put forward.

The difference between the two structures might be expected to give entirely different properties to the two states of iron, the α and the γ . It was interesting that there was no difference between the α and the β forms, but it might be supposed that the lattice structure was not the only determining factor. It might be that at a certain temperature a change in the arrangements of the surface forces in the atom took place. In fact, there must be a change of some sort in the atom, because the magnetic properties were so entirely different on the two sides of the critical point. Experiments with X-rays showed that when iron was magnetised there was no disturbance of the position of the atoms, and it was necessary to suppose that when iron passed from the magnetic to the non-magnetic state it was because of some change in the atom

¹ *Physical Review*, 1917, vol. x. p. 681.

² 1 Ångström unit = 10^{-8} centimetre.

and not due to any modification from the position of the atoms which would require a different lattice form.

Dr. Westgren had discussed the arrangement in a certain specimen of manganese steel with the object of determining whether or no the carbon atoms replaced some of the iron atoms in the face-centred arrangement, or whether the metal atoms iron and manganese alone went to the formation of the lattice, the carbon atoms being separately inserted forming no part of the structure, but certainly distorting it. The author inferred from his experiments that the latter suggestion had the greater plausibility. There were at least two ways in which an attempt might be made to decide between the various alternatives. If carbon atoms really entered into combination with iron atoms forming new crystals of perhaps different structure, new lines ought to appear on the photograph plate. That had not been the case, although, of course, they might be too faint to see. A second method would consist in estimating the specific gravity of each suggested form of architecture. That would be rather a difficult method although a considerable degree of accuracy in measuring the X-ray spectra had been reached, but so far, however, as the results went, they were in agreement with the conception that the carbon atoms were merely intruded into the structure, which was actually built out of the atoms of iron and manganese. That point might be seen from considerations differing rather from those of Dr. Westgren. Supposing that the face-centred unit cube contained the four metal atoms proper to such an arrangement, and taking the iron and manganese atoms in such proportions as to agree with the weight percentages quoted, it could be readily shown that the sum of the atomic weights of all the atoms in the cube multiplied by the known weight of a hydrogen atom was equal to 378.4×10^{-24} . That weight included four metals atoms, and the proper proportion of carbon, silicon, &c. The specific gravity was stated to be 7.83: thus if a were the edge of the cube—

$$\begin{aligned} a^3 \times 7.83 &= 378.4 \times 10^{-24} \\ a &= 3.64 \times 10^{-8} \text{ cm.} \\ &= 3.64 \text{ \AA.U.} \end{aligned}$$

If the iron atoms (supposing them all to be iron for the moment) had been in actual contact, the distance from centre to centre would have been 2.47, as Hull found it to be in the α modification, and the edge of a cube would have been $2.47 \times \sqrt{2} = 3.49 \text{ \AA.U.}$ That could be interpreted in the sense that if the iron and manganese atoms had been there alone the sides of the cube would have been 3.49. The insertion of the carbon atoms had opened up the structure without altering the general arrangement, and the length of the side had grown by 0.15 \AA.U.

The figures given by Dr. Westgren showed that there was about one carbon atom to every seventeen metal atoms. In the face-centred arrangements the biggest empty spaces were those which had their

centres at the middle point of each side of the cube, and the middle point of the cube itself. In the cube made by iron atoms the largest sphere which could be inserted in such a hole would have a diameter of 1.1 \AA.U. ; the carbon atom was known to have a diameter of 1.54 \AA.U. : thus if a carbon atom was forced into every one of those holes that particular side of the cube would be stretched by about 0.44 \AA.U. In any line of iron atoms parallel to the edge of a cube, the filling up of about four spaces in ten would give the right number of carbon atoms in the steel as described. That would imply a stretch equal to about 0.18 \AA.U. , which was of the order actually found to exist. Such a calculation could only be looked upon as provisional, since some of the assumptions on which it was based were not definitely proved; still it was clear that Dr. Westgren's idea was plausible.

To sum up, it seemed not unlikely that the stresses and strains within a material would eventually be calculable from known forces between atom and atom. These might be varied by some rearrangement within the atom, so that the nature of a substance might be changed without altering the lattice form; which would also imply a change in properties and, it might be, a very considerable one. He (Sir William Bragg) thought that those new methods of examination would eventually lead to metallurgical investigations beginning with the atoms themselves as units and built upwards from the atomic stage. The work seemed to be extremely important, and it was much to be regretted that more had not been done in England. For that a simple reason might be given—the shortage of workers. The demands made on scientific men had been very great since the end of the war. Two years ago he had started in his laboratory investigations of the same kind as those described in the paper, but the men had been drawn away by much better offers to other regions of industrial science. He hoped, however, that there would be a change for the better. If anything he had said would induce men to turn their attention to those lines of research he would be very glad indeed.

Professor ARNOLD (London) said that Sir William Bragg might like to know that metallurgists had very solemnly buried β -iron at a meeting held some years ago, and he was glad Sir William had found no remains of it in the lattice frame. As to the manner in which carbon existed in manganese steel, it existed as a mixture of carbide of iron and carbide of manganese, as shown by chemical examination. He would like to refer to the extraordinary case of the alloys of manganese and iron, which he (Dr. Arnold) had lately been studying. There was the extraordinary result that if iron had 1 per cent. of manganese it gave about 40 per cent. elongation on 2 inches; if 10 per cent. of manganese it would give 1 per cent. elongation; if 20 per cent., it gave an alloy which turned yellow and went back to the 40 per cent. elongation like the 1 per cent., and with 30 per cent. of manganese there was 60 per cent. of elongation and a yellow metal like brass. That was almost

as baffling as the lattice forms, but if the lattice forms would throw any light on a fact like that it would be very important.

Dr. W. ROSENHAIN (National Physical Laboratory) said it had been a very delightful privilege to listen to Sir William Bragg, and he wanted as far as he could strongly to enforce what Sir William had said as to the real future advancement of our knowledge of the internal structure of metals lying in that direction of X-ray analysis. The paper of Dr. Westgren contained a set of conclusions which he thought would be completely established ultimately. He did not think Dr. Westgren considered they were quite finally established, but no doubt they would be, and they would have a very direct bearing on certain questions upon which a good deal of controversy had taken place in the past. On the whole they confirmed in a remarkable manner the evidence of other methods of investigation. Referring for a moment to β -iron, that was of course a name for a certain condition of iron which existed, although it had been long known—and Dr. Westgren confirmed it—that its crystal structure was identical with α -iron. At the same time, it was non-magnetic and there was a change of energy in passing from the non-magnetic to the magnetic state, and Dr. Westgren treated that question in a very philosophical and scientific manner, and did not attempt to dogmatise about it. With regard to the whole question of applying X-ray analysis to the study of the physical properties of materials, while it was undoubtedly an extremely powerful method of attacking problems from the inside, it had to be remembered that a knowledge of the structure of the crystal was not the whole story by a very long way with regard to the properties of metals, and it was just on that very point he thought Dr. Westgren made the one possible mistake in his paper. For instance, he said on p. 323 that he found in martensite the space lattice of α -iron, and that was personally what he himself should have expected to find, but Dr. Westgren concluded that therefore the difference in hardness between martensite and ordinary annealed iron was not due to the iron but was due to the carbon. Then he found that the carbon, apparently, was not present in any crystalline form. That conclusion might be true, but it was not proved by his evidence, because it had to be remembered that all that the evidence proved was that there were regions in the sample which he had examined in which the α -iron space lattice existed, and that those regions were large enough to give a visible spectrum. What their real size was Dr. Westgren was not able to say, and so far as the indications went the suggestion was that the regions were very minute. It did not follow in the least that the whole of the martensite consisted of material having that particular space lattice, or any definite geometrical lattice at all; all that the author had proved was that there were particles which were at least crystallites. There might be larger things, but he had certainly established that there were crystallites of α -iron in martensite. He himself would venture to suggest that probably that was the

fact—that there were probably only minute crystallites of α -iron, and that the remainder of the material was probably not in a crystalline condition at all. If it were, he should have expected—and he hoped Sir William Bragg would correct him if he was wrong—that Dr. Westgren would have found the spectra of other crystals, but he had conspicuously failed to find them. That being the case, there was either the alternative that the remainder of the carbon was forced into the α -iron lattice—and from all that was known of the behaviour of α -iron relative to carbon that seemed extremely unlikely—or that the α -iron crystallites were surrounded by non-crystalline material, which might be largely iron and which certainly contained carbon, but whether in combination with iron or not it was not possible to say. If that were the case, it gave a very full explanation of the properties of martensite. There were the magnetic properties due to the presence of α -iron crystallites, but those crystallites were very minute and were embedded in the relatively unyielding mass of non-crystalline material, and their response to magnetising force was hindered. It took a larger amount of magnetising force to bring them into the magnetic condition, and once in that condition they retained it with much greater power. There was a high coercive force and high remanence. Mechanical hardness was accounted for in precisely the same way, namely, by the existence of a comparatively large amount of non-crystalline material which was incapable of undergoing plastic deformation by the process of crystal slip. Consequently it might be supposed that the hardness of martensite was due, as an extreme case, to the same kind of hardness that was obtained in the hardening of iron by cold work. Some results Mr. Whiteley had obtained showed that the chemical reactions of hardened steel were very much like those of cold-worked steel, and that further supported the view. He did not want to go into the whole question of the theory of hardness, but he thought it was worth while pointing out that the results obtained by Dr. Westgren added very distinct weight to that suggestion, because they were entirely consistent with it and thoroughly inconsistent with almost every other hypothesis of the nature of martensite that had been put forward. With regard to the question of the carbides and the position of carbon in manganese steels or other steels which essentially consisted of γ -iron, he had been intensely interested in Sir William Bragg's exposition. Only a week ago he himself had ventured to put forward, with a good deal of trepidation, some consequences from a view as to the cause of the hardness of solid solutions generally, based upon the idea that by forcing into the space lattice of pure metal atoms of another metal, not necessarily by forcing them into the interstices in the way Sir William Bragg suggested, but by actual substitution, in some cases, in the original piling of the metal, a certain degree of hardening would result, and the degree would depend roughly on the solubility of the element added. That led to the very interesting conclusion, which he thought was borne out by fact, that the amount of hardening which the addition of a metal

B produced in a metal A was at a rough first approximation inversely proportional to the solid solubility of metal B in metal A. Roughly speaking, that was true of a very large series of alloys, including the alloys of iron. That emphasised once again the enormous importance and the really sweepingly fundamental effect which research of that kind was capable of having on our conceptions of metals, but it had to be remembered that, even when the whole story about the structure of a crystal was known, one had yet in dealing with metals to consider materials which were aggregates of many crystals, and metallurgists were quite as much interested in the substance which existed between the crystals holding them together as in the crystals themselves. It was necessary to recognise the limitations of X-ray analysis, and that in the Hull method particularly a statistical result only was obtained. It gave evidence that certain space lattices existed, but so far no indication of the size—or only a very indirect indication of the size—of the particles in which they existed or the manner in which they were held together.

Sir ROBERT HADFIELD, Bart., Past-President, said he had been greatly pleased to see that Dr. Westgren had shown that the statements made years ago with regard to β -iron were not correct. He was not questioning the great utility of the controversy that went on over α and β forms of iron at that time. It had, however, always seemed to him, especially after his experience with manganese steel, that such steel helped to prove the incorrectness of the theory. Manganese steel was very peculiar. Although it was non-magnetic, it was possible to have manganese steel in a condition so that it had in it 40 per cent. of specific magnetism as compared with pure iron. That was very remarkable, and was largely due, he thought, to what had been mentioned by Professor Arnold, the condition of the carbides. There were carbides present in manganese steel, and he thought the magnetic qualities were due to the precipitation of the carbides present. If they were once released the iron became normal, and then it was possible to get over 40 or 50 per cent. specific magnetism. A bar could be made in which one end was practically zero in specific magnetism and the other end by heat treatment had 40 per cent. specific magnetism. He had received an interesting letter from Dr. Westgren a few days before, which it might be useful to read as part of the discussion. Dr. Westgren had come forward freely and said that one of his statements in the paper was open to correction. He wrote: "The suppositions on the constitution of cementite that I present have proved wrong as the result of my later investigations. The arrangement of atoms in Fe_3C has turned out to be more complicated than I thought I could conclude from the first spectrograms, which were rather indistinct. From later very clear spectrograms, however, I infer that a close relationship must exist between the arrangements of atoms of Fe_3C and of γ -iron. Unfortunately, I have not yet been able completely to explain the Fe_3C spectrograms, but I hope to do so

shortly." It was to be hoped that that meant another paper from Dr. Westgren on that very important point. It showed that he had not been able to clear up the point and that he freely admitted that, and no doubt there would be many alterations in the theories presented before the solution was arrived at. He was quite convinced in his own mind, and was delighted to find Sir William Bragg was of the same opinion, that it was in that direction that a solution of many of the problems which puzzled metallurgists to-day would be found, and from which important advances would proceed. He congratulated Dr. Westgren most heartily on his able paper, which was but another proof of the very great importance of Swedish science in metallurgy.

Dr. C. A. EDWARDS (Swansea) said that, having had something to do with the theories that had been put forward relating to the possible causes of hardness produced by quenching, he was naturally particularly interested in the observations made on p. 323, and he wished quite candidly to confess that the results described in the paper did clearly necessitate a modification of the views he himself had been responsible for. There was no doubt that the views he had hitherto held relating to the constitution of martensite did not appear to be correct. Work of the kind described in the paper would be materially helpful in arriving at the true explanation of why steel was hardened as the result of quenching operations, and he hoped that the admirable work so ably done through the initiative of Sir William Bragg and his son would be continued, so far as it was possible.

Dr. F. C. THOMPSON (Manchester) said the Institute was to be very greatly congratulated on receiving what was one of the firstfruits of a new scientific method applied to metallurgical problems, and especially, perhaps, upon the opportunity the members had had that morning of receiving from Sir William Bragg his account of the formation of solid solutions. With regard to the allotropy of iron, so far as it was dealt with in the paper, he was afraid he refused to be converted even now to the view that β -iron had no existence. It was necessary to find an explanation of the magnetic changes and an explanation of the sudden energy change which took place on cooling, and he failed to see how it was possible to explain those things adequately without assuming some form of allotropy for β -iron. What Dr. Westgren had shown, however, was that the allotropy was of a different kind from the allotropy between α -iron and γ -iron, and that led to two alternative explanations. Measurements which had been made did not, as far as he could see, put out of court the possibility of a discontinuous change in the atomic distance of the iron as it passed from the α to the β stage. There was also the strong possibility that the electronic structure of the atom was really responsible for the change itself. In either case he still failed to see that β -iron, as a definite modification, was shown to have no existence whatever. The other point of very great

importance which had been raised was in connection with the structure of martensite. Especially in the work that had been done on the non-magnetic nickel steel which was quenched in liquid air and then was shown in a martensitic condition to consist of both α and γ iron, there was a final proof of the view of martensite which had been held by a certain section of metallurgists for a long time, namely that it consisted essentially of a solution of Fe_3C in α -iron together with a certain variable amount of the unchanged γ -iron remaining behind. In the case of the nickel steel, Dr. Westgren had shown definitely that that was, as far as the modifications of the iron at any rate were concerned, the actual structure which was obtained. It was of interest that in the case of plain carbon steel he was unable to find any γ -iron. That did not necessarily mean that no γ -iron was present, and certainly he (Dr. Thompson) found it difficult to agree with Dr. Westgren's fourth conclusion, in which he said that in martensite iron was in the form of α modification. All that Dr. Westgren could say was that there was no γ -iron present sufficient in quantity to be detected by the method used. In reading the paper it would be found that in the case of fairly high carbon steel he was unable to find any lines indicative of the carbon contained in the steel, and that simply meant that the method was not suitable for the determination of small quantities of materials which were present. The method, therefore, did not put out of court the possibility of γ -iron being present in the martensite of a plain carbon steel. It only showed that the amount of γ -iron was less than could be detected by the method used, quite a different matter. He was interested in what had been said with regard to the solid solutions, but was rather surprised to hear that Dr. Rosenhain had a week or so ago put forward as new the view that the distortion of the space lattice was responsible for the hardness of solid solutions, because he himself had put forward that view to the Faraday Society several years ago.¹ He was pleased to find now that Dr. Rosenhain agreed with the opinions he had himself expressed. The only other point he wished to mention was that some work he was doing in connection with carbide of iron had shown that there was certainly in most steels a mixture of the high temperature and low temperature forms of cementite. The change from one to the other on cooling was a fairly sluggish one, and in practically all the cementite in commercial steels the mixture of the two modifications was present. That conclusion was drawn chiefly from electrical resistivity measurements, and was interesting in connection with the communication Sir Robert Hadfield had just read, in which Dr. Westgren found some difficulty in explaining the space lattice of cementite. It was possible that the difficulty which he was experiencing in that direction was due to the fact that he was examining a mixture of the two forms of carbide and in that way getting certain complexities. It was possible to use the method of X-ray analysis in connection with

¹ *Transactions of the Faraday Society*, 1916, vol. xii. Part I.

measurements such as coefficients of expansion as had already been done in the case of sodium chloride, and in the paper itself sufficient data were given to calculate the mean coefficient of expansion of iron up to about 800°C . The data actually gave a value of about 2.2×10^{-5} . It was a value which was not very closely in agreement with that which was generally accepted at the present time, but it was of course of very considerable interest. Its rather appreciable deviation from other values offered some suggestion of a change of atomic distance on passing from α to β iron.

Mr. A. HALLIMOND (London) said one point raised by Sir William Bragg in connection with the paper was the question of whether there existed in the space lattice any trace of chemical combination. He believed that had been the subject of a great deal of controversy. To some extent the point had been met by the subsequent qualification of that part of the paper. Still, the matter was a very important one, and he could not help thinking a good many workers had gone further than the facts warranted in putting forward the view that in the space lattice there was no trace of chemical combination. There were certain groups of atoms which absolutely necessitated the assumption that the chemical molecule continued to exist in the space lattices, so there was no reason to abandon the view that in martensite the molecule of Fe_3C might be present. The lines of evidence were briefly : (1) The evidence to be derived from the ultra-violet spectra which were characteristic of chemical grouping. (2) In the realm of inorganic chemistry there was an excellent example of the same thing in the compounds of the uranyl group. (3) Another piece of evidence was the great diversity of the crystalline forms of the organic compounds. A point that occurred to him as one on which research was very greatly required, and which was being developed to a certain extent on the Continent, was the question of how diffusion occurred. The general picture of a space lattice was of a rigid lattice which did not, at first sight, seem to afford any opportunity for the diffusion of molecules from one part of the lattice to the other. In γ -iron the carbide could travel rapidly, and other substances, such as phosphorus, travelled at a slower rate. There was therefore a necessity for some means of reconciling the rapid translation of substances through the lattice, which occurred just as in liquids, with the apparent rigidity of the lattice theory. Finally, he felt himself very much in agreement with some remarks made by Dr. Rosenhain. As a result of Sir William Bragg's work there had been developed a law of constancy of atomic distance, which implied that the distance between the atoms in all the space lattices was, for each kind of atom, a fairly definite constant. A good deal of energy had to be given to a lattice to diminish or increase that distance to an appreciable extent. It was evident, therefore, that the extent of the inter-atomic compression in mixed crystals, for example, might represent a very considerable energy content before it was possible to detect by the X-rays any change in the spatial relationship of the

lattice. There was therefore the possibility of both physical and chemical variations in energy which were not to be detected by means of the X-ray analysis as it at present existed.

CORRESPONDENCE.

Dr. WESTGREN wrote, in reply, that he was very grateful for the valuable and kind remarks made in the discussion on his paper. He was especially pleased that the eminent pioneer on that special sphere of research, Sir William Bragg, had agreed to present the paper to the Institute.

He regarded as very plausible the hypothesis of Sir William, that the ferro-magnetic properties of iron were connected with a certain arrangement of the surface forces in the atom. However, as the magnetic condition of the iron in the range of temperature 0° to 900° C., according to what had been shown by several investigators,¹ was undoubtedly a continuous function of the temperature, there evidently did not occur any sudden spontaneous change in the arrangement of those atom forces at a certain critical point. He therefore considered that the disappearance of the ferro-magnetism at about 768° C. could not justifiably be regarded as evidence of an allotropic change of the iron at that temperature. As Sir William suggested, the properties of a substance depended, of course, not only on the relative position of the atoms, but on the qualities of the atoms as well. If a sudden change in the qualities of the atoms occurred at a certain temperature, that would evidently mean an allotropic change of the substance even if the space-lattice was unchanged. However, as he (Dr. Westgren) knew of no instance where such a sudden change of the atom properties by heating or cooling had been manifested, he had ventured the statement that allotropic transformations of solid crystalline substances were always connected with a change of the arrangement of their atoms.

Dr. Thompson had suggested that perhaps a sudden change in the distance between the atoms took place at A2. Dr. Westgren considered this possibility to be inconsistent with the results obtained by Benedicks² from his extremely accurate measurements of the dilatation of iron. Should there be any discontinuity in the curve in the vicinity of A2, that would be only $\frac{3}{1000}$ of the one, which arises at A3. The slight, continuous deviation that Benedicks found at A2 might be explained by a change in the magneto-striction at that temperature.

In the discussion the main interest evidently centred on the question

¹ P. Curie, *Thèse, Gauthiers-Villars*, Paris, 1895; P. Weiss and G. Foëx, *Archives des Sciences*, 1911, Nos. 1, 2, vol. xxxi. pp. 5, 89; K. Honda, *Journal of the Iron and Steel Institute*, 1915, No. I. p. 199.

² *Journal of the Iron and Steel Institute*, 1914, No. I. p. 407.

of the orientation of the carbon atoms in the hardened steels. Dr. Westgren was much pleased to see that Sir William Bragg's extremely interesting calculation on the structure of the austenitic manganese steel had given a result corresponding to his own supposition, namely, that the carbon atoms of the steel were inserted into the space-lattice, formed by the metal atoms. He pointed out, that it might be of interest to make some closer investigations into the matter by examining a series of austenitic steels with constant nickel or manganese content, but with varying content of carbon.

Against Dr. Rosenhain's supposition that martensite consists of α -iron crystallites embedded in a substance of non-crystalline material containing the carbon atoms, he wished to point out that such a conclusion could not justly be drawn from the spectrograms of martensite obtained. It was certainly true that α -iron was the only crystalline substance that gave any visible lines in the spectrograms. As mentioned on p. 321, an annealed steel containing 1.25 per cent. carbon, that was about 18 per cent. Fe_3C , however, did not give any other lines than those belonging to the ferrite, although such a steel certainly contained cementite crystals, which fact he (Dr. Westgren) had confirmed later by chemical isolation and roentgenographic analysis of the same. He had found from the spectrograms of cementite that that substance had a very complicated structure. According to the theory of the Debye-Scherrer method, the cementite therefore must give rise to less distinct lines in the spectrogram than the very simply built α -iron. In view of that circumstance the fact could easily be accounted for that any interference lines of the cementite could not be detected in the spectrogram of the hardened carbon steel SKF 1, although that steel as a hypereutectoid one certainly contained globules of free cementite when quenched at 760°C . Whether carbon atoms were inserted into the α -iron crystallites of the martensite could not be decided on the basis of the experimental results so far obtained. However, he hoped to be able to contribute to the solving of that problem later by taking spectrograms with greater precision on which a calculation of the same sort as the one Sir William Bragg had made on the manganese steel could be executed.

He (Dr. Westgren) had recently read a very interesting article by Dr. Rosenhain¹ on the hardness of solid solutions, and he considered the hypotheses developed there to have a very great likelihood. Similar opinions regarding the theory of hardening have lately been put forth by Zay Jeffries and R. S. Archer² in a highly valuable paper. He was almost entirely of the same opinion as those authors regarding the causes of the hardness of martensite. Contrary to the view of so many investigators who had dealt with the problem of hardening, he did not find it necessary to think that the α -iron

¹ *Proceedings of the Royal Society*, 1921, vol. xcix. p. 196.

² *Chemical and Metallurgical Engineering*, June 15, 1921, p. 1057.

crystallites were surrounded by a layer of an amorphous material to account for the hardness of the martensite. That amorphous state of iron he thought to be of a rather hypothetical nature, and the very important part attributed to it in many metallurgical problems did not appear to him to be justified. As Jeffries and Archer pointed out, an important cause of the hardness of the martensite certainly must be ascribed to the extreme minuteness of its grains, but he also believed that a just as weighty reason for the hardness should be sought in the possible fact that foreign atoms or atom complexes inserted into the α -iron crystallites acted as keys, hindering the free interference slip. He did not wish to go deeper into that matter now, as he found it more advisable to wait for the illumination of the problem that might be given by more thorough Röntgen analytic investigations.

Sir Robert Hadfield had quoted a letter from him concerning the structure of cementite. Unfortunately he (Dr. Westgren) evidently had not expressed himself clearly enough in his letter, and Sir Robert had misunderstood him. His observations on the constitution of cementite did not refer to what had been set forth in the present paper, where he had made no attempts to demonstrate how the cementite was built. The paragraph in his letter, read in the discussion, was meant as a correction of some suppositions he had put forth in a communication to *Jernkontoret* in Stockholm a year ago. Therein he had been incautious enough to conclude from the first rather indistinct spectrograms obtained with copper anticathode that the cementite probably had a cubic and rather simple structure. From later spectrograms, however, which contained a great many lines it could be seen that the cementite, in fact, was built up in a very complicated way. He thought there was very little likelihood that Dr. Thompson's supposition was correct, namely, that the investigated samples of cementite consisted of a mixture of two different forms of the carbide, as he (Dr. Westgren) had obtained quite the same spectrograms for cementite from three very different materials. One was a steel of lamellar pearlitic structure, one contained the cementite only in a very strongly developed network, and one was a white pig iron.

He had found that out of the $\sin^2 \frac{\theta}{2}$ values of the cementite there could be arranged several series formed by successive small integer multiples of constant quantities. That simple affinity of the values indicated that the cementite belonged to the cubic system. An expression of the type $k (h_1^2 + h_2^2 + h_3^2)$ that represented all the $\sin^2 \frac{\theta}{2}$ values was, however, found to have such a small constant k that the base group of Fe_3C must consist of 27 molecules, *i.e.* 108 atoms. It had not been possible to calculate the arrangement of so many building-stones in the elementary cube. He hoped to be able to give further information on that matter later on.

Iron and Steel Institute.

COMPARISON OF DIFFERENT METHODS OF ESTIMATING SULPHUR IN STEEL.

By T. E. ROONEY (NATIONAL PHYSICAL LABORATORY, TEDDINGTON).

THIS work has been undertaken with the object of ascertaining whether it is necessary to anneal the drillings used in the volumetric estimation of sulphur, in order to obtain results which are in agreement with results obtained by standard gravimetric methods.

Great assistance has been derived from the excellent bibliography in the *Journal of Industrial and Engineering Chemistry*, December 1916, by H. B. Pulsifer.

The first reference to the annealing of a sample before estimating the sulphur occurs in 1885, where Rinman¹ annealed white iron in a crucible before applying the colorimetric determination.

In 1902, George T. Dougherty² gave results obtained by an improved annealing on six samples, and in the same year Walters³ and Miller annealed samples of pig iron and shot metal in a current of hydrogen or natural gas, before using the evolution method.

In 1903, C. A. Seylor⁴ annealed cast iron at 750° C. for fifteen minutes, and used concentrated hydrochloric acid for the solution of the sample.

In 1904 there was another paper by Dougherty,⁵ and in the same year S. S. Knight⁶ recommended annealing in iron dust.

In 1906, McFarlane and Gregory⁷ annealed pig irons and shot iron with cream of tartar.

In 1911, T. G. Elliott⁸ annealed nickel-chromium steels at 800° C. with potassium ferrocyanide. This is the first reference, as far as the author is aware, to the annealing of steel samples

¹ *Jernkontorets Annaler*, vol. xl. p. 362.

³ *Eng. Soc. West. Penn.*, vol. xviii. p. 83.

⁵ *Iron Age*, vol. lxxiii. No. 13, p. 3.

⁶ *Iron and Steel Magazine*, vol. vii. p. 487.

⁷ *Chemical News*, vol. xciii. p. 201.

⁸ *Journal of the Iron and Steel Institute*, 1911, No. I. p. 412.

² *Iron Age*, vol. lxix. p. 14.

⁴ *Analyst*, vol. xxviii. p. 97.

before estimating the sulphur by the evolution method. This method was recommended for nickel-chromium steels and other self-hardening materials.

DESCRIPTION OF METHODS AS USED IN THIS RESEARCH.

The methods compared by the author were as follows: Archbutt's Gravimetric Method,¹ a Gravimetric Method communicated by Mr. Huxley of Vickers, Ltd., and the Volumetric Method as used at the National Physical Laboratory.²

Archbutt's Method.

Five grammes of steel drillings added to a warm mixture of 25 c.c. HCl (1·10 sp. gr.) and 35 c.c. HNO₃ (sp. gr. 1·42). When the reaction subsides a few crystals of KClO₃ are added and the mixture digested until complete solution of the steel is obtained. The liquid is then evaporated until a skin is formed, when 30 c.c. HCl (sp. gr. 1·10) are added and the mixture evaporated to dryness, but not baked for any length of time. The beaker is allowed to cool, 40 c.c. of HCl (sp. gr. 1·10) added, and the mixture heated until solution is complete. The liquid is again evaporated until a skin is formed, 5 c.c. of HCl (sp. gr. 1·10) added, the whole diluted with water to double the volume. It is then filtered into a small beaker and the filter washed with small quantities of water. The beaker is warmed on a steam bath, 10 c.c. of 10 per cent. BaCl₂ added, and left on the steam bath for two hours. It is afterwards allowed to stand overnight, filtered, and the filter washed first with a dilute solution of BaCl₂ and HCl and then with water, until free from BaCl₂, when it is ignited and weighed. The final volume of the solution is kept below 100 c.c.

Method as Communicated by Mr. Huxley of Messrs. Vickers, Ltd. (Method for Sulphur (long method).)

Five grammes of steel dissolved in 30 c.c. HNO₃ + 30 c.c. HCl; evaporate to dryness; bake for five minutes; dissolve up in 30 c.c. HCl and evaporate again to dryness; bake for ten minutes;

¹ *Journal of the Society of Chemical Industry*, vol. ix. p. 25.

² *Journal of the Iron and Steel Institute*, vol. lxxvi. 1908, No. I. p. 102.

dissolve up in 30 c.c. HCl; evaporate to a paste, and while the paste is still capable of being shaken round add 6 c.c. HCl and warm at a low temperature until the paste is in solution. Dilute with about 100 c.c. hot water and filter off silica; wash paper once with 4 per cent. HCl wash. To the filtrate add 10 c.c. of a solution of potassium sulphate (1.25 gramme per litre), also 15 c.c. barium chloride (200 grammes per litre), make up to 200 c.c. with water and gradually bring to boiling. Directly the solution boils remove to a warm plate and allow to digest for an hour and stand in the cold overnight. A blank on the acids and potassium sulphate is done with 0.1 gramme bar iron and taken through the same stages and the result deducted.

Volumetric Method. (As used at the National Physical Laboratory.)

Five grammes of steel drillings are dissolved in 70 c.c. of HCl (sp.gr. 1.10) and the gases evolved are passed through 70 c.c. of an acid solution of cadmium acetate. The cadmium acetate solution containing the cadmium sulphide is filtered. Ten c.c. of standard iodine solution is placed in the precipitation flask and the cadmium sulphide is washed off the filter paper into this solution. The mixture is shaken round, any cadmium sulphide adhering to the sides of the flask is washed down, and the excess of iodine is titrated with standard $\text{Na}_2\text{S}_2\text{O}_3$ in the usual way.

In carrying out the above process, using HCl of sp. gr. 1.10, it is essential that the speed of solution should be as quick as possible, and care should be taken that an undue amount of HCl is not driven over into the precipitation flask. It is now generally accepted that the use of weak solutions of hydrochloric acid for the solution of the drillings gives rise to the formation of organic sulphides which are not absorbed by the cadmium acetate solution and necessitate the use of a hot tube for their decomposition.¹ Many workers on this account prefer to use concentrated hydrochloric acid, but experience at the National Physical Laboratory has shown that no appreciable amount of organic sulphides is formed by the use of hydrochloric acid of specific gravity 1.10.

¹ *Journal of the American Chemical Society*, vol. xvii. p. 891; *Stahl und Eisen*, vol. xvii. p. 486 and also p. 489.

This is confirmed in the curves given in *Stahl und Eisen*.¹

In the present research both concentrated hydrochloric acid and acid of specific gravity 1.10 have been used with practically no difference in results, but when using the concentrated acid it is necessary to use a washing flask to prevent hydrochloric acid gas from being carried into the precipitation flask.

While looking up references it was noticed that there was a slight difference in the details of Archbutt's method as used at the National Physical Laboratory and as published in the *Journal of the Society of Chemical Industry*. It was the custom at the National Physical Laboratory to use 10 c.c. of BaCl_2 solution in the final precipitation, whereas the quantity as given in the *Journal of the Society of Chemical Industry* is 5 c.c. Results of determinations on twelve steels, using 5 c.c. and 10 c.c., are given in Table I. :

TABLE I.—*Sulphur Determinations by Archbutt's Gravimetric Method.*

Marks.	5 c.c. BaCl_2 .	10 c.c. BaCl_2 .
	Sulphur per Cent.	Sulphur per Cent.
Ax.	0.017	0.020
I.T.PL.	0.022	0.026
T.G.M.	0.024	0.026
G.N.T.	0.031	0.035
35	0.032	0.036
L.	0.026	0.032
0.09	0.016	0.023
SS.	0.007	0.013
44	0.034	0.040
48	0.037	0.050
49	0.036	0.037
50	0.052	0.055

Samples of thirty-three commercial straight carbon steels have been examined and a few typical results are shown in Table II. The steels vary fairly widely in composition, the lowest carbon being 0.10 per cent., ranging up to a maximum of 1.2 per cent.

In column 4 of the table are shown the results obtained by the volumetric method on drillings heated over a Meker burner. The drillings were wrapped in two 11 cm. filter papers and placed

¹ Vol. xxviii. p. 249.

in a porcelain crucible covered with a lid and heated for twenty minutes. Column 5 shows the results obtained on drillings which were annealed at 750° C. for twenty minutes in a current of nitrogen or hydrogen. The annealings in this case were carried out in a silica tube, heated electrically, and the actual temperature of the drillings measured with a pyrometer.

Difficulties may arise owing to the uneven distribution of the sulphur in the steel, as, for example, in sample marked T.G.M. in Table II., but the difference observed on any one sample in the percentages of sulphur as determined by the different methods is not greater than would be obtained by a number of determinations by the same method on the same sample.

TABLE II.—*Percentages of Sulphur in Commercial Carbon Steels as obtained by Different Methods.*

Marks.	Gravimetric.		Volumetric.		
	Archbutt's Method.	Huxley's Method.	Unannealed.	Annealed Meker.	Annealed N. 750° C. 20 minutes.
Ax. .	0·020	0·020	0·021 0·022	0·022 0·023	...
I.T.P.	0·026	0·026	0·026 0·027	0·024, 0·028 0·026, 0·032	0·024 } 650° C. 0·025 }
T.G.M.	0·026 0·031	0·026 0·028	0·034, 0·034 0·030, 0·028 0·028, 0·028 0·030	0·026, 0·030 0·029	0·034, 0·031 0·034, 0·027
G.N.T.	0·035	0·035	0·036 0·034	...	0·036 0·035
B.S. .	0·058	...	0·054, 0·057 0·055, 0·058	0·058 0·058	...
0·09 .	0·023	0·023	0·025 0·025	...	0·024 0·025
SS. .	0·013	0·014	0·017 0·017	...	0·014 0·015
44 .	0·040	0·039	0·041 0·041	0·042 0·042	0·042 H. 0·041
50 .	0·055	0·052	0·055 0·058	0·056 0·055	0·057 H. 0·056

Having failed so far to obtain a straight carbon steel which showed a variation in the percentage of sulphur, as determined gravimetrically and volumetrically, on unannealed drillings, it was next attempted to produce such a result by various treatments.

For this purpose pieces were cut from a sample of steel and subjected to the following treatments:

N. Normalised by heating to 900° C. for twenty minutes and cooling in air.

Q. Heated to 900° C. for twenty minutes and quenched in cold water.

Q.T. Heated to 900° C. for twenty minutes, quenched in cold water, and tempered for twenty minutes at 600° C.

C. Cold-worked by hammering with a hand sledge, the reduction in thickness being about 50 per cent. on a $\frac{1}{4}$ -inch slab.

The following results were obtained by the volumetric process:

	N.	Q.	Q.T.	C.
As drilled	0.031 0.032	0.031 0.032	0.029 0.029	0.031 0.032
Drillings annealed at 750° C. in N for twenty minutes	0.031 0.033	...	0.032 0.030	...

The same sample of steel was also machined in different ways and the sulphur determined on each sample:

	Shapings.	Turnings.	Millings.
Volumetric	0.033 0.032	0.030 0.031	0.031 0.031
Gravimetric, Archbutt's	...	...	0.031

Finally a steel of fairly high sulphur content (0.063) was taken and the drillings annealed at various temperatures in an atmosphere of nitrogen and also of hydrogen.

About 100 grammes of drillings were taken, well mixed, and portions annealed in nitrogen at temperatures ranging from 450° to 1050°. Practically no difference was observed on determining the sulphur in each portion.

In carrying out the annealings in nitrogen and hydrogen, a rapid stream of the gas was passed through the apparatus to sweep out the air, and then slowed down to a very slow rate while

the heating of the sample was in progress, otherwise a loss of sulphur might occur in the case of hydrogen, especially at the higher temperatures.

The escaping gases were passed through a solution of cadmium acetate so as to detect any such loss, but no appreciable amount of precipitate was formed in any case.

Having occasion to redetermine, by the evolution method, the sulphur in a sample of steel millings, which had been stored for some time, the result obtained was found to be much lower than that found a month or so previously. With a view to finding the reason for the discrepancy, the sulphur was determined by the evolution method on a number of straight carbon steels, drillings or millings of which had been stored for some time. Those which gave a lower sulphur figure after storing were found, on examination of the drillings or millings under a hand lens, to have small spots of rust here and there on the surface.

It was found that the sulphur figure, as obtained by evolution, was restored to its proper value by annealing with filter paper in an atmosphere of nitrogen, but annealing in an atmosphere of nitrogen without the filter paper was not satisfactory.

The results of these experiments are given in Tables III. and IV.

A fairly large quantity of millings was machined from one of these steels, well mixed and placed in two bottles, and sulphur determinations made on the contents of each bottle. Both bottles were then securely corked and one was sealed with ceresin wax. The unsealed bottle was opened from time to time and the sulphur was determined by the evolution method. At first very little difference was observed, but after a time the results became erratic, and it was observed with a hand lens that slight rusting had commenced. Finally, after a further interval fairly constant figures were obtained for the sulphur by the evolution method, but these were lower than the figures obtained on the fresh millings. On annealing a portion of the sample in nitrogen, the low percentage of sulphur was still obtained by the evolution method. On annealing another portion of the millings wrapped in a filter paper and in an atmosphere of nitrogen, the same percentage of sulphur was obtained as originally given by the fresh millings.

The sealed bottle was now opened and the same figure was obtained for the sulphur content by the evolution method as when the bottle was first sealed up. The results are given in Table V.

CONCLUSIONS.

Annealing the drillings of ordinary commercial carbon steels before estimating the sulphur by the evolution method is not necessary in the great majority of cases, unless the drillings have been stored for some time and incipient rusting has taken place, or unless the presence of elements like titanium is suspected.

Annealing the drillings may be necessary with steels low in manganese and containing chromium, which are liable to contain oxides which may form a eutectic with the sulphide.¹

TABLE III.

Sample No.	Evolution on fairly Fresh Millings.	Sulphur (Gravimetric).	Evolution after Storing.	Evolution on Annealing Stored Sample 800° C. in N for Twenty Minutes with Filter.
1	0.070	0.072	0.062	0.071
3	0.071	0.072	0.065	0.071
5	0.067	0.069	0.059	0.066
7	0.072	0.072	0.068	0.073
11	0.066	0.067	0.057	0.066
13	0.037	...	0.033	0.037
15	0.027	0.028	0.024	0.027
16 ²	0.028	0.026	0.028	0.027
17 ²	0.026	0.024	0.027	0.027

TABLE IV.—*Sulphur Evolution.*

Fresh Millings.	After Storing.	Anneal in N without Filter.	With Filter.	Gravimetric.
0.072	0.067	0.068	0.072	0.070
0.037	0.034	0.035	0.038	0.038
0.038	0.033	0.033	0.037	0.037

¹ Whiteley, *Journal of the Iron and Steel Institute*, 1920, No. II.

² No sign of rusting.

TABLE V.

Date.	Unsealed Jar.		Sealed Jar.		Remarks.
	'Sulphur Evolution.	Sulphur (Grav.).	Sulphur Evolution.	Sulphur (Grav.).	
Mar. 29	0·072	0·070	0·069	0·071	Annealed with filter paper in nitrogen.
May 13	0·065	...	...	...
„ 14	0·068	...	...	...
„ 17	0·070	...	...	...
„ 27	0·071, 0·070	...	...	...
„ 27	0·072	...	...	...
Aug. 19	0·069, 0·067 0·067, 0·066 0·066	...	...	...
„ 25	0·066, 0·067 0·067	...	...	...
Oct. 5	0·065, 0·066	...	0·070, 0·071 0·070, 0·071	0·071	
„ 5	0·072	0·071	Annealed with filter paper in hydrogen.

EXPERIMENTS WITH NICKEL-CHROMIUM STEELS.

A number of nickel-chromium steels were experimented with next. The compositions of these steels are given in Table VI.

TABLE VI.

	C.	Si.	P.	Mn.	Ni.	Cr.
2086 . . .	0·30	0·10	0·030	0·46	1·81	0·88
3870 . . .	0·36	0·18	0·041	0·60	3·36	1·01
9263 . . .	0·56	0·16	0·033	0·73	trace	0·52
4377 . . .	0·29	0·15	0·035	0·55	5·11	0·60
C . . .	0·37	0·25	0·030	0·31	0·15	12·37
E . . .	0·24	0·02	0·013	0·34	4·47	1·02
F . . .	0·29	0·20	0·014	0·46	3·90	1·14

The results of the sulphur determinations on these steels are given in Table VII.

TABLE VII.

	Archbutt's Method.	Huxley's Method.	Volumetric (Unannealed).
2086	$\left\{ \begin{array}{l} 0.034^1 \\ 0.032^1 \end{array} \right.$	0.032	0.034
3870	$\left\{ \begin{array}{l} 0.045 \\ 0.046 \end{array} \right.$	0.044	0.044
9263	0.023 ¹	0.025	$\left\{ \begin{array}{l} 0.025 \\ 0.025 \end{array} \right.$
4377	0.029	0.029	$\left\{ \begin{array}{l} 0.031 \\ 0.031 \end{array} \right.$
C	0.032	$\left\{ \begin{array}{l} 0.034 \\ 0.031 \end{array} \right.$	$\left\{ \begin{array}{l} 0.033 \\ 0.033 \end{array} \right.$
E	0.044	0.043	$\left\{ \begin{array}{l} 0.042 \\ 0.042 \end{array} \right.$
F	0.033	0.030	$\left\{ \begin{array}{l} 0.033 \\ 0.033 \end{array} \right.$

Three samples of 3870 were then taken and subjected to the following treatment:

- (1) Quenched from 830° C., tempered at 600° C., and cooled slowly in furnace.
- (2) Quenched from 830° C., tempered at 600° C., and quenched in water.
- (3) Cold-worked by hammering on two opposite faces, the piece being reduced in thickness from $\frac{3}{4}$ inch to about $\frac{5}{8}$ inch.

TABLE VIII.

	Sulphur. Vol. Unannealed.
1	0.044
2	0.047
3	0.045

Some drillings of a nickel-chromium steel, kindly provided by Dr. Hatfield of the Brown Firth Research Laboratories, and having the following composition: Carbon, 0.66; nickel, 2.06; chromium, 2.14; silicon, 0.15; and manganese, 0.16, gave the results shown in Table IX.

It will be noted that this steel is relatively high in chromium and carbon, and low in manganese content.

It will be noted in Table IX. that some of the samples were annealed with potassium ferrocyanide as recommended by

¹ Needed careful digestion and a long time for complete solution. The concentrated acid used in Huxley's method dissolves these steels readily.

T. G. Elliott. The highest result obtained, 0.048 per cent., is still far short of the gravimetric figure obtained of 0.078 per cent., but the fact that the drillings were unduly thick will probably account to some extent for the difference.

TABLE IX.

Temp. of Annealing in Nitrogen.	Time.	Strength of HCl used.	Sulphur per Cent. obtained as Cd. S.	Sulphur per Cent. Residue in Flask.	Remarks.
...	...	1.1 sp. gr.	0.012	0.061	
...	...	conc.	0.011	...	
Mecker	20	1.1	0.017	...	
800	20	conc.	0.030	...	
800	20	"	0.034	...	Ann. with pot. ferro- cyanide
800	75	"	0.037	...	"
850	30	"	0.041	...	"
880	40	"	0.041	...	"
900	20	"	0.043	...	"
900	40	"	0.030	...	Without ferrocyanide
900	40	"	0.034	...	" "
and quenched					
900	40	"	0.039	...	With ferrocyanide
and quenched					
900	40	1.1	0.044	0.028	" "
900	40	conc.	0.045	...	" "
900	40	"	0.048	...	" "
slow rise					
900	40	"	0.044	...	" "
slow rise					
900	40	"	0.046	0.026	" "
slow rise & fall					
900	40	"	0.045	...	
900	75	"	0.042	...	
920	40	"	0.042	...	
1000	20	"	0.034	...	

In using Elliott's method, difficulty had previously been experienced in the readiness with which the sample, mixed with potassium ferrocyanide, absorbed sulphur from the gases when the heating was carried out by means of coal-gas. This was more especially the case when a gas muffle was used. In fact, it is essential in any method of annealing to take great care that sulphur is not absorbed from some outside source during the process.

EXPERIMENTS WITH HYDROGEN.

An experimental annealing in hydrogen was carried out on 10 grammes of the same steel. The stream of hydrogen was maintained at a fairly rapid rate during the heating, and the escaping gases were passed through a solution of cadmium acetate. The temperature was raised to 1000°C . from cold in about forty minutes, and was maintained at an average of 1020°C . for about fifty minutes. The maximum temperature attained was 1040°C . The formation of cadmium sulphide in the absorbing solution was first noticed about 950°C ., but very little was formed until the higher temperatures were reached.

After cooling the drillings were well mixed, divided into two portions, and treated in the following manner: *1st portion*.—The sulphur was determined gravimetrically. *2nd portion*.—The amount of sulphur evolved as sulphuretted hydrogen in the evolution method was estimated and a gravimetric sulphur estimation was carried out on the contents of the evolution flask.

TABLE X.

	Sulphur per Cent.
Evolved as H_2S on annealing in H	0.015
Estimated by gravimetric method on portion 1 of drillings	0.063
Estimated by evolution method on portion 2 of the drillings	0.037
Gravimetric estimation on contents of flask	0.026

In view of the results of the foregoing experiments it was thought that a micro-examination might yield some useful information in conjunction with the chemical examination, but unfortunately the steel was only available in the form of drillings. Another piece of a nickel-chromium steel was therefore obtained through the kindness of Dr. Hatfield. The composition of this steel was as follows: Carbon, 0.15 per cent.; nickel, 3.84 per cent., chromium, 0.39 per cent.; manganese, 0.32 per cent.; silicon, 0.05 per cent.; phosphorus, 0.034 per cent.

The results of the sulphur determinations are given in Table XI.

TABLE XI.

			Sulphur.		
Gravimetric	.	.	0.040,	0.039	
Evolution, unannealed	.	0.031, 0.032, 0.031, ¹	0.035, ¹	0.037 ¹	
Evolution after annealing in N with pot. ferro-cyanide and filter paper :					
At 700° C. for 20 minutes	.	.	0.031, ¹	0.032	
„ 750° C. „ 20	„	.	0.035, ¹	0.034	
„ 750° C. „ 30	„	.		0.034 ¹	
„ 780° C. „ 30	„	.	0.034,	0.033, ¹	0.035 ¹
„ 800° C. „ 20	„	.	0.037, ¹	0.033, ¹	0.036
„ 800° C. „ 40	„	.		0.032	
„ 830° C. „ 15	„	.		0.031 ¹	
„ 850° C. „ 20	„	.		0.028 ¹	
„ 900° C. „ 20	„	.		0.030 ¹	
„ 900° C. „ 40	„	.	0.032, ¹	0.033,	0.033

A microscopic examination of a portion of the steel revealed the fact that the inclusions consisted of at least two constituents, one of which was much darker than the other.

Various heat treatments were carried out on portions of the steel, including quenching and tempering from various temperatures, but no difference could be observed in the character or distribution of the inclusions after these various treatments.

Although, owing to the lack of suitable samples, no definite conclusions can be arrived at from these experiments on nickel-chromium steels, it was thought that the results obtained would be of some interest.

Of the nine samples examined only two are of the type which yield low results in the sulphur estimation by the evolution method, and from the experiments carried out it appears that this condition cannot be produced in the finished steel by mechanical or heat treatment.

To determine the cause of such a condition in nickel-chromium steels it would be necessary to have a number of such steels, the history of which could be traced right back to the melting stage, in form and quantity suitable to enable further experiments to be carried out.

In conclusion, the best thanks of the author are due to Dr. Rosenhain, F.R.S., for valuable advice and encouragement during the course of the work.

¹ Very thin millings.

CORRESPONDENCE.

Mr. J. H. WHITELEY (Stockton-on-Tees) wrote that in both the gravimetric methods described in the paper the drillings were dissolved in a mixture of nitric and hydrochloric acids. That procedure, he believed, was extremely risky, since loss of sulphur might occur during the initial stages of the solution of the sample. It was much safer to add the nitric acid first and then the hydrochloric acid cautiously to it. The use of a cadmium salt in the volumetric method was also liable to give low results if the absorbing solution containing the sulphide was exposed to strong daylight or to direct sunlight during the process. For that reason he preferred the use of zinc salts instead of cadmium. The author would find full particulars of a large number of experiments he (Mr. Whiteley) made some years ago on those and other questions relating to the estimation of sulphur in the *Proceedings of the Cleveland Institution of Engineers*, 1913-1914.

In the experiment described on p. 344, in which the steel was cold-worked by hammering with a hand sledge, the author appeared to have adopted an unnecessary procedure, because he subsequently drilled his sample. Drilling was, of itself, a very severe method of cold-working.

Mr. ROONEY wrote, in reply to Mr. Whiteley, that the method of adding the nitric acid first, and then adding the hydrochloric acid cautiously to it, had been tried at the National Physical Laboratory on many occasions, but the results obtained did not vary appreciably from those obtained by the Archbutt method. The trouble experienced was that the addition of the nitric acid first rendered the drillings passive and solution was much more difficult. It might be as well to state that at the National Physical Laboratory a 1300 cubic centimetre beaker provided with a cover glass was used in the estimation. A much more serious source of loss, in his opinion, was in the digestion of the mixture before proceeding to evaporate. More especially with cast irons, large discrepancies occurred if the digestion was not sufficiently prolonged or carried out at too high a temperature. It was best to digest on the side of a hot plate until the bulk of the fumes had condensed or disappeared before proceeding to evaporate on the hotter parts of the plate.

He was unfortunate in not having had the opportunity of reading Mr. Whiteley's paper until a few months ago, otherwise he would have included in the comparison some of the methods recommended by Mr. Whiteley.

The use of cadmium acetate solution free from chlorides had been found satisfactory, but the precipitate of cadmium sulphide should be filtered and transferred to the absorbing solution as quickly as

possible. It was interesting to note that zinc salts were to be preferred to cadmium on account of the action of light, but it was doubtful whether zinc sulphide would withstand the atmosphere of a steel analysis laboratory any better than cadmium sulphide, a point which was of great importance.

With regard to cold-working by hammering with a sledge-hammer, there was a possibility that cold-working the mass of the sample in that way might produce a different effect from that produced by drilling.

In conclusion, he was glad to have Mr. Whiteley's criticism of the details of the methods, but would have liked to have had his opinion with regard to the annealing.

Iron and Steel Institute.

“SLIP-LINES” AND TWINNING IN
ELECTRO-DEPOSITED IRON.

BY W. E. HUGHES, B.A. (CAMP.).

INTRODUCTION.

THE author was led to an investigation of the presence or absence of “slip-lines” in electro-deposited iron by a remark of J. C. W. Humfrey.¹ Mr. Humfrey says (*op. cit.*, p. 82): “A polished and etched section of a slab² examined under the microscope showed a very irregular structure, the crystals in the edge nearest the cathode being exceedingly minute but gradually increasing in size as they grew outwards from it. The surface of the crystals, after etching, showed peculiar wavy markings and also numerous cavities, probably filled with electrolyte.” After annealing at about 1000° C. for two or three hours and then slowly cooling, the surfaces of the crystals ceased to show the wavy markings referred to.

Upon examination by the present author of numerous samples of electrolytic iron, wave-like markings were found upon the polished and etched surfaces of many of them. Fig. 1 is illustrative. Whether the markings observed by Mr. Humfrey and by the author are of, so to say, the same genus and due to the same cause is not, however, clear. Mr. Humfrey does not appear to have pursued any investigation as to their nature; and the markings shown in Figs. 1 and 2, Plate VII., of his paper do not very closely resemble those seen by the author in his specimens, and which he believes to be “slip-lines.”

“Slip-lines” have been closely studied, and an explanation of their nature and mode of origin given, by Ewing and Rosenhain.³ Their explanation appears to have received general assent. While the present author is not satisfied with that explanation in its

¹ *Carnegie Scholarship Memoirs*, 1912, vol. iv. p. 80.

² *i.e.* of iron electro-deposited from the Fischer-Langbein FeCl_2 - CaCl_2 solution.

³ *Philosophical Transactions*, 1900, p. 353; *ibid.*, 1901, p. 279; and *Proceedings of the Royal Society*, 1899, vol. lxxv. p. 85.

entirety,¹ the term "slip-lines" is used here because it denotes a well-known feature of the structure of metal. The object of this paper is to show that "slip-lines" (whatever their nature) occur in electro-deposited iron.

EXPERIMENTAL.

The deposits of which micrographs are shown were formed, some in a sulphate and some in a chloride of iron solution. Particulars of the deposition are given in the table. The deposits were all formed upon small cylindrical cathodes cut from solid metal rod, sometimes steel, sometimes brass; they were of different thicknesses and structures. It is unnecessary to give further experimental details here.

References to Figs.	Type of Solution.	Current Density. Amp./ Ft. ² .	Temperature. Degrees C.	Remarks.
1, 2	Sulphate ² . Acid = 4.5 N.	(Mean) 75	65 to 72	Cathode stationary during deposition.
3	Sulphate . . . Acid = 0.018 N.	65	76	"
4	Sulphate . . . Acid = 0.001 N.	22	13	"
5	Chloride ³ . Neutral.	114	116 to 118	"
6, 7, 8	Chloride . . . Neutral.	120	103	"
9, 10	Chloride . . . Neutral.	120	103	Cathode moving during deposition.

DESCRIPTIVE.

The photomicrographs show various samples of electro-deposited iron. As will be seen from the table, some of the

¹ Prof. C. A. Edwards has recently expressed some doubt or "wonder" as to whether there may not be an alternative explanation. See "The Physico-Chemical Properties of Steel," 1920, p. 131.

² Ferrous ammonium sulphate.

³ Ferrous calcium chloride.

specimens were deposited from the sulphate bath, and some from the chloride solution. The conditions of deposition are given in the table. The general appearance of the lines, which are believed to be "slip-lines," differ according to—(i.) Whether they are viewed at low or at high magnification; (ii.) the general structure of the deposit; and (iii.) the amount of etching the specimen has received.

(i.) When the deposit has been formed upon a cylindrical cathode, the lines, at low magnifications, and especially when the deposit is of the fibrous type, appear as wavy annular rings which sometimes run completely round the specimen (Figs. 1 and 2, Plate XX.). At higher magnifications and on broader crystals the appearance is similar to the so-called "herring-bone" structure clearly seen in the augite constituent of certain gabbros¹ (Figs. 6 and 8, Plates XXI.–XXII.). When more deeply etched, the appearance at high magnification resembles a staircase (Fig. 9, Plate XXII.).

(ii.) When the deposit is not of the fibrous type the lines do not give to the deposit the appearance of being composed of innumerable strata as seen in Fig. 2. The longitudinal axes of the crystals (or grains) not being parallel, but more or less inclined to one another, the lines have no regular relation in general appearance—no regular relation, that is, from grain to grain; but on individual grains the "herring-bone" structure can be seen (Fig 10, Plate XXII.).

(iii.) The amount (depth) of etching causes, as is natural, a marked difference in appearance. The exceedingly thin lines produced by light etching become broadened when the iron is more deeply etched; and this, at high magnifications, causes the staircase appearance to be particularly marked.

The following conclusions may, it is suggested, be drawn from the features illustrated in the photomicrographs:

(a) The lines are common to deposits from both the chloride and the sulphate solutions.

(b) They are formed whether the deposition is conducted at high or at low current density.

(c) The temperature of deposition does not seem to determine whether the lines are present or absent.

¹ *Vide* A. Harker, "Petrology," 1895, p. 61, Fig. 13.

(d) They are found in deposits of various thicknesses. In the actual specimens deposited and examined the thickness of the deposits varied from 0.015 inch to 0.005 inch.

So far, then, as the conditions of deposition—namely, nature of electrolyte, temperature, and current density—are concerned, the formation of the lines does not seem to be dependent upon them. Nor is it dependent upon the thickness of the deposit.

There is, however, one type of deposit in which such lines are not formed, or, at any rate, are not to be observed at magnifications up to 1800 diameters. Deposits formed in a bath containing much suspended matter and many small particles do not appear to show the lines, unless indeed the cathodes are sharply moved during the formation of the deposits. The result of the movement seems to be to prevent the oxide particles suspended in the solution from settling down upon and becoming, consequently, included in the deposit to anything like the same extent as happens in the case of the stationary cathode.

DISCUSSION OF THE RESULTS.

The proposition which it is sought to establish is as follows : Certain lines (circumferential in the cases of deposits formed upon cylindrical cathodes) are frequently to be seen in electrolytic iron which resemble the lines called " slip-lines " which are a characteristic of over-strained metal ; and these lines (seen in electrolytic iron) are " slip-lines," and are caused by the stresses, of considerable magnitude, which operate in the iron during its deposition.

The micrographs shown and already considered are, it is suggested, sufficient to manifest the kind of lines indicated. They are very noticeable to an observer of a specimen of electro-deposited iron when examining the metal with the microscope. If the grains are narrow their general appearance, at quite low magnifications, is that of continuous circumferential division lines ; but, under higher powers, each line is seen to be made up of very small straight lines, any pair of which are inclined at an angle to one another, so that the whole line has a zig-zag appearance. When the grains are large, and v-shaped, the lines on each grain often have a " herring-bone " appearance even at lower magnifications.

In the first place it has to be considered whether the lines seen in the deposited metal sufficiently resemble those seen in strained metal and known as "slip-lines." This is a matter of observation and comparison. Though perhaps not very clear in some cases, the resemblance is manifest in very many others, and particularly so in the majority of the photographs shown. In Fig. 3, Plate XX., especially the change of direction from grain to grain is marked; and further, each complete grain (of the fibrous form in this case) appears as a twin crystal, and the lines change abruptly in direction from one half of the twin to the other.

The second question to be answered is: Is it at all possible that the lines illustrated and described can indeed be "slip-lines"?

"Slip-lines" are the result of stress, mediately or immediately.¹ Hence, if such lines exist in electrolytic iron, this must have been the locus of stress. There is very good evidence that this is the case.

(i.) As long ago as 1877 Mills pointed out that when metals are deposited electrolytically on the bulb of an ordinary thermometer the mercury in the stem is seen to rise.² This shows that there is a pressure acting upon the bulb—a pressure that must result from the contraction of the deposit, since it can have no other cause. Mills called the pressure "electrostriction"; and by measuring the mechanical pressure necessary to cause the same rise of the mercury as was caused during the formation of any particular deposit he obtained a value for the total pressure exerted by that deposit upon the thermometer bulb. In this way Mills obtained for iron a value, namely, eighteen atmospheres, as the "extreme effect" exerted during its formation by a deposit of that metal upon the thermometer bulb. In some remarks on his experiments (which, in the case of iron, were conducted at a temperature of 17° to 18° C.), he says: "If we conceive such pressure to be produced by the electric deposition of successive layers of metal (as was actually the case with thermometer 502), it seems reasonable to suppose that each of the layers will have nearly the same constrictive effect. The first layer, however,

¹ Cf. Ewing and Rosenhain, *op. cit.*, and G. Tammann, *Zeitschrift für physikalische Chemie*, 1912, vol. lxxx, p. 687.

² *Proceedings of the Royal Society*, 1877, vol. xxvi. p. 504.

constricts the bulb alone; the second constricts the first also; the third its predecessors; and so on. Hence, the observed effect upon the bulb should diminish at compound interest."

(ii.) The same phenomenon was observed by E. Bouty, independently and without a knowledge of Mills' work, and was considered in a number of papers in the *Comptes Rendus*.¹ As the result of his experiments Bouty concludes that: (a) Electrodeposits exercise considerable pressures upon the base metals on which they are formed. (b) The pressure increases with increasing thickness of deposit. (c) The slight local elevation of temperature is too insignificant to account for the rise of the mercury, when the deposit is formed upon a thermometer bulb. (d) Current density is not the determining factor. It is interesting to note that Bouty remarks that "very crystalline or coarsely granular deposits exercise but insignificant compression," and further that, in his view, the compression is due to the change of volume which the metal undergoes upon deposition. It is unnecessary to enter in detail into a consideration of Bouty's researches. It seems sufficient for the purpose of this paper to note that Mills' observations were confirmed (and extended) by an independent investigator and by like means.

(iii.) A paper by G. G. Stoney² seems to be the next in order of date dealing specifically with the phenomenon under immediate consideration.³ Stoney deposited nickel on one side of a steel rule which was "stopped off" on the other side. The deposited metal caused the rule to be bent into a concave form, the nickel being on the side of lesser radius. Stoney then calculated, mathematically, the force necessary to produce a given amount of flexion. The maximum figure he found for the tension of nickel is given as 19.2 tons per square inch. This figure will be referred to later.

(iv.) V. Kohlschütter and E. Vuilleumier⁴ in their paper "On Cathode Processes during Metal Separation" have also observed and measured the amount of bending (towards the anode) caused

¹ *Comptes Rendus*, 1879, vol. lxxxviii. p. 714; *ibid.*, vol. lxxxix. p. 146; *ibid.*, 1880, vol. xc. p. 987; and *ibid.*, 1881, vol. xcii. p. 868.

² *Proceedings of the Royal Society*, 1909, vol. lxxxii. p. 172.

³ Dr. Mills has kindly informed the author that, so far as he knows, no other work on the subject had been published until Stoney's paper.

⁴ *Zeitschrift für Elektrochemie*, 1918, vol. xxiv. p. 300. For further work on this subject, see H. Stäger, *Helvetica Chimica Acta*, 1920, vol. v. p. 584.

in a metal strip by nickel deposited upon one side of it. Their work shows the existence of considerable forces, namely, of contraction, during the formation of deposited metal; but their purpose was other than Stoney's, and they were not concerned with the determination of the actual magnitudes of the forces in question.

It is suggested that the researches referred to above establish beyond doubt that electro-deposited metal is the locus of forces variously named pressure, tension, or electrostriction, and, further, that these forces are of very considerable magnitude. They show, too, that the force is one of contraction. The evidence of observations that can be made in almost any plating-shop where it is the practice to deposit such metals as iron, nickel, or cobalt, is enough in itself to prove the operation of internal forces in the deposited metal. Deposits are often observed to split and crack. In the case of nickel especially, the deposit, after splitting, will sometimes leave the base metal upon which it is formed and curl over upon itself. The cracks to be often seen in deposited iron have been referred to and illustrated elsewhere.¹ It is a fact of note that cracks are less frequently seen in deposits of the softer metals such as silver, copper, or gold.

The third question is—Are the forces located in deposited metal of an order of magnitude great enough to produce “slip-lines”? Upon this point the work of O. Faust² and of F. Credner³ is illuminating. Faust gives a photomicrograph of electro-deposited copper⁴ which shows beyond doubt “slip-lines” (*Gleitlinien*) in that metal. He mentions the work of Mills and Bouty and, with reference thereto, makes the following observations: “According to Mills’ results these pressures are quite considerable. In the case of copper they can amount to 109 atmospheres: according to Bouty they can amount to as much as 350 atmospheres (476 kilogrammes). These pressures are in any case more than twice the value of the lower elastic limit found for ordinary copper, and it seems likely that in their action they are comparable with simple mechanical treatment.” Indeed, when the figure given by Stoney (for nickel) is recalled, there

¹ *Journal of the Iron and Steel Institute*, 1920, No. I, p. 321.

² *Zeitschrift für anorganische Chemie*, 1912, vol. lxxviii. p. 20.

³ *Zeitschrift für physikalische Chemie*, 1913, vol. lxxxii. p. 457.

⁴ Reproduced in Professor Tammann’s “*Lehrbuch der Metallographie*,” 1914.

seems no reason to doubt that the forces that operate in deposited metal would be sufficient to effect a slipping upon planes of relative weakness—even in the case of iron.¹ At the same time it has to be said that, so far as the author is aware, there are no exact data that show that the forces existent in deposited iron are of a magnitude of the same order as the value of the elastic limit of ordinary iron or steel.

Allusion was made above (p. 358) to the fact that the lines considered to be " slip-lines " do not appear to occur in deposits containing a great deal of included matter—oxide or, according to Macfadyen,² carbon. The explanation of this seems to be that the crystal grains have, in such case, no opportunity of growing to any considerable size. The deposit consists of a mass of very small, irregularly placed grains with oxide situate along the greater length of the boundaries. No doubt pressures operate during the formation of such deposits: the fact that anything resembling " slip-lines " has been unobserved in the grains of these deposits is probably due to the smallness of the grains.

ON THE APPEARANCE OF TWINNING IN DEPOSITED IRON.

The reference (p. 359) to the abrupt change in direction, in one and the same grain, of the lines called " slip-lines " occasioned the use of the term " twin." The opinion in regard to the formation of twin crystals does not appear to be definitely settled. The discussion upon Professor C. A. Edwards' recent paper³ is sufficient to show this. Under the circumstances, therefore, and in view of the fact that he has not been able to give sufficient study to this interesting subject, the author ventures to merely call attention to the feature that appears to be twinning in Figs. 3, 4, 6, 8, and 10 especially (Plates XX.—XXII.). The point is, of course, that in the case of the iron deposits, while there was certainly mechanical stress, there was no annealing. It would be difficult to suppose that annealing could occur at such temperatures as those at which the deposits were formed. Even the higher temperatures, 103° and 118° C., would, it is suggested, not suffice

¹ Assuming " slip-lines " or " slip-bands " are really due to actual slip.

² *Transactions of the Faraday Society*, 1920, vol. xv. p. 98.

³ *Journal of the Institute of Metals*, No. 2, 1915, vol. xiv. p. 116.

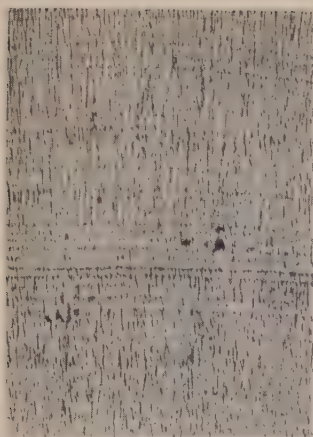


FIG. 1.

Deposit showing annular or "wavy"
lines at low magnification.
× 150.



FIG. 2.

Lines (a) due to interruption of the deposition
can be distinguished from "slip-lines" (b) in this
photograph. × 150.



FIG. 3.

Annular or "wavy" lines at higher magnification.
Twinning and "slip-lines" are both visible.
× 450.

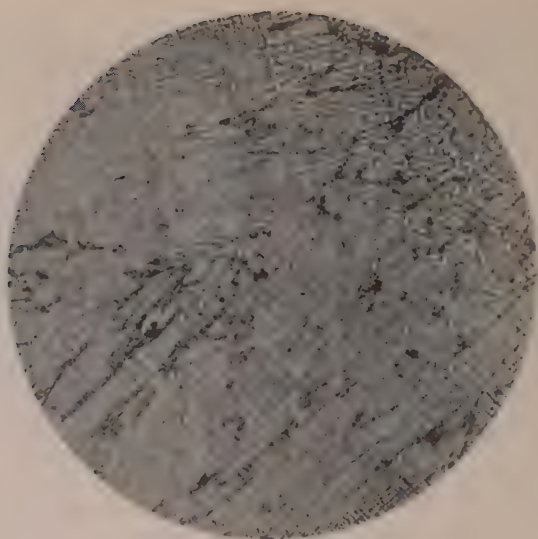
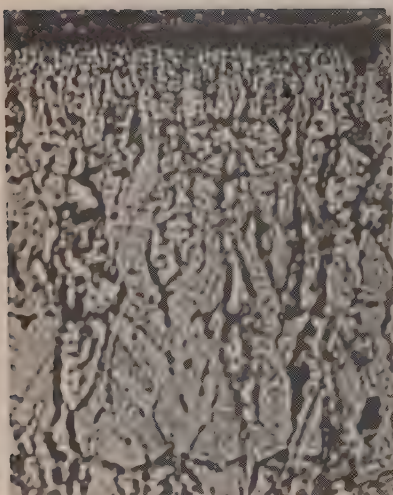


FIG. 4. $\times 300$.

base metal \rightarrow



outer part
of deposit

FIG. 5

"Slip-lines." $\times 800$

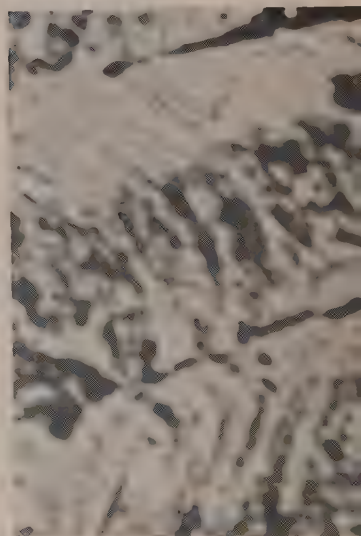


FIG. 6

"Slip-lines" and twinning. $\times 800$



FIG. 7. $\times 450$.



FIG. 8. $\times 650$.



FIG. 9. $\times 1000$.



← base metal

outer part
← of deposit

← casting
metal

FIG. 10. $\times 150$.

to cause in iron any such molecular rearrangement as would become evident in its structure ; still less would the lower ones, 22° to 65° C., be sufficient.

SUMMARY.

Photomicrographs of etched sections of electro-deposited iron, deposited under various conditions, are shown which exhibit certain peculiar lines or markings that appear sometimes, and especially at low magnification, as wave-like lines running through the mass of the metal, and sometimes, on individual grains, in herring-bone arrangement. It is suggested that these lines are "slip-lines," which are produced in the grains of which the deposit is composed by the forces of contraction that act in it during its formation.

The author has once again to express his sincere thanks to Professor H. C. H. Carpenter, F.R.S., for his continued kindly advice and encouragement during the work, which was carried out under the Professor's general supervision. The author's thanks are also due and expressed to Professor Lamb, D.S.C., M.Sc., of the Engineering School, East London College, for permitting him to use the apparatus in his laboratories.



Iron and Steel Institute.

THE PROTECTION OF IRON WITH PAINT
AGAINST ATMOSPHERIC CORROSION.

By J. NEWTON FRIEND, D.Sc., Ph.D., F.I.C., CARNEGIE GOLD
MEDALLIST (BIRMINGHAM).

THE results described in this memoir are a continuation of those already detailed by the author in 1918.¹ The general method of experimentation was the same, and all the precautions which previous research had shown to be necessary in order to obtain consistent results were rigidly adopted. The method consisted in exposing, for a period of five years, series of plates of steel coated with various paint mixtures, and determining their loss in weight due to corrosion.

The plates measured 2 feet by 1 foot in area and 0.03 inch in thickness (No. 22, B.W.G.), and were made of open-hearth steel, cold-rolled and charcoal annealed. They were cleaned by immersion in dilute sulphuric acid in leaden baths, then washed and placed for a few minutes in dilute caustic soda solution to remove any traces of acid. After again washing and drying the plates were finally polished with emery-paper. After having been weighed and painted, the plates were suspended on a specially constructed wooden fence erected on a low bank running almost due north and south in the valley of the Severn near Worcester, and the author gladly takes this opportunity of thanking the Worcester City Sewage and Waterworks Committee for allowing him free use of this ground.

In order that the results might be as reliable as possible, and relatively independent of the effects of minor variations in chemical and physical properties from which iron plates are so liable to suffer, five plates were used in each test. Unfortunately, during the absence of the author on military service, some of the plates were, during gales, blown down from the fence and damaged. This accounts for the gaps in the table of results at the end of this memoir.

¹ *Iron and Steel Institute : Carnegie Scholarship Memoirs, 1918.*

After five years of exposure to the atmosphere the plates were removed, soaked in caustic soda solution to remove the paint, washed, dried, and any adherent rust removed by gentle scraping and polishing with emery-paper. The cleaned plates were now weighed, and their loss in weight taken as a measure of their corrosion.

The oils used in this research were obtained from Messrs. Mander Brothers of Wolverhampton, several of them being specially prepared for the author by Dr. Morrell. They were as follows :

No. 1. Pure Calcutta raw linseed oil.

No. 7. Oil No. 1, heated for sixteen hours to a maximum temperature of 305° C. No drier.

No. 8. Oil No. 1, heated for four hours with 0·5 per cent. Cyprus umber up to 305° C.

No. 9. Oil No. 1, heated for two hours with 1·5 per cent. manganese hydroxide to 150° C.

No. 10. Oil No. 1, heated for four hours with 1 per cent. litharge to 205° C.

INFLUENCE OF OIL TREATMENT.

In the author's previous paper attention was drawn to the superiority of polymerised linseed or litho oils over the raw oil for the protection of iron against atmospheric corrosion. This is attributable in part to their diminished permeability towards water, but mainly to their greater stability, polymerisation resulting in the saturation of their double bonds, thus rendering them less liable to oxidation and disintegration upon exposure.

On the other hand, an ordinary boiled oil is partially oxidised in the process, and, particularly if a drier be present, a marked increase in the rate of setting is observed when the oil is spread as a paint film upon a suitable surface. One of the main objects of the "boiling," indeed, is to increase the rate of setting. But the same catalysts which accelerate the setting or initial oxidation also accelerate the disintegration or slow further oxidation upon prolonged exposure to air. Hence, in contradistinction to litho oils, ordinary boiled oils will not as a rule offer as good protection to iron as the raw oil. This is clearly demonstrated by the results of Series XL. to XLIII.

MULTIPLE COATS.

It has already been demonstrated ¹ that not only do two coats of paint protect iron from atmospheric corrosion more efficiently than one thinner coat, but they are even slightly more efficient than one thick coat containing the same weight of paint as the two together.

It is important to remember that this applies only to atmospheric corrosion, for the author has shown ² that a precisely opposite effect is obtained by prolonged immersion of iron plates in water. The amount of corrosion under these conditions actually increases with the number of coats or thickness of the paint. This has been fully confirmed during recent years, and the author hopes to publish these results at an early date, together with an explanation for this anomaly.

The question now arises as to whether or not the method of mixing and applying a paint to iron may not influence the results. To determine this series of plates were given two coats of paint, namely :

Series XLVI. Two coats of 45 per cent. Venetian red paint.

Series XLV. One coat of 30 per cent. Venetian red paint followed by one of 60 per cent.

Series XLIV. One coat of 60 per cent. Venetian red paint followed by one of 30 per cent.

It will be observed that the total weight of both pigment and oil on each plate in the three series is the same, but the results are strikingly different.

Series XLV. yields by far the best results, the thin coat apparently clinging tenaciously to the surface of the metal, whilst the outer coat, containing a high pigment and low oil percentage, protects the inner by reason of its greater resistance to permeability by moisture and to mechanical erosion.

¹ *Iron and Steel Institute : Carnegie Scholarship Memoirs*, 1918.

² *Ibid.*, 1913, vol. v.

TABLE OF RESULTS.—*All Weighings are expressed in Grammes.
Period of Exposure—five years.*

Series.	Composition of Paint by Weight.	Weight of Paint on each Side.	Plate No.	Loss in Weight.	Mean Loss.
XL.	60 red lead 40 oil No. 1	15	236	3.35	3.63
			237	5.95	
			238	3.05	
			239	3.50	
			240	2.30	
XLI.	60 red lead 40 oil No. 7	15	241	...	4.87 omitting No. 242
			242	(12.30)	
			243	5.25	
			244	5.82	
			245	3.55	
XLII.	60 red lead 40 oil No. 9	15	246	...	6.91 omitting No. 248
			247	7.20	
			248	(17.77)	
			249	...	
			250	6.62	
XLIII.	60 red lead 40 oil No. 10	15	251	...	5.45
			252	3.80	
			253	6.58	
			254	7.10	
			255	4.30	
XLIV.	First coat :	12	256	...	2.66
	60 Venetian red		257	2.25	
	40 oil No. 8	258	2.48	2.66	
	Second coat :	259	...		
	30 Venetian red	260	3.25		
XLV.	First coat :	12	261	1.35	1.30
	30 Venetian red		262	1.80	
	70 oil No. 8	263	...	1.30	
	Second coat :	264	...		
	60 Venetian red	265	0.75		
XLVI.	40 oil No. 8	12 each	266	...	2.13
	Two coats :		267	...	
	45 Venetian red		268	2.28	
	55 oil No. 8		269	1.45	
			270	2.65	

SECTION II.

*NOTES ON THE
PROGRESS OF THE HOME AND FOREIGN
IRON AND STEEL INDUSTRIES.*

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In the preparation of these Notes the Editor has been assisted by L. P. SIDNEY,
Assistant Secretary, and others.

IRON ORES

AND OTHER METALLIFEROUS ORES USED IN THE IRON AND STEEL INDUSTRY.

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I.—GEOGRAPHICAL DISTRIBUTION OF ORES.

(Arranged in alphabetical order under Countries.)

Algeria.—B. Simmersbach, *Mining Industry of Algeria and the Iron Ore Company Mokta-el-Hadid* (Zeitschrift für praktische Geologie, February 1921, vol. 29, pp. 27–30). The article gives a short account of the metalliferous mining industry of Algeria, and, in particular, of the iron ore mining developments and operations of the mining company of Mokta-el-Hadid, the most important in the country.

Brazil.—*The Zircon Deposits of Sao Paulo* (L'Age de Fer, July 10, 1920, vol. 36, p. 439). Zircon is said to occur in inexhaustible quantities in the northern districts of the State of Sao Paulo in Brazil, the average composition of the mineral being given as:

	Per Cent.
Oxide of zirconium	88.7
Silica	7.1
Oxide of iron	4.1
Oxide of titanium	0.6

The grade of mineral for export is 70 per cent. ZrO_2 as a minimum, and the exports in 1918 amounted to 2085 tons. The various industrial applications of zirconium are briefly referred to.

H. E. Williams, *Chromite Deposits of Bahia, Brazil* (Engineering and Mining Journal, February 26, 1921, vol. 111, pp. 376–378). Particulars are given of the deposits in the Santa Luzia district.

Bulgaria.—G. Schmid, *A Manganese Occurrence near Jamboli in Bulgaria* (Zeitschrift für praktische Geologie, March 1921, vol. 29,

pp. 43-44): The author had occasion in 1918 to examine a manganese mine at Jamboli, on behalf of the German Commission for the supply of raw materials. The deposits are said to possess little economic value, except under the abnormal conditions due to the war. The ore is classed as polianite, and contains from 30 to 45 per cent. of manganese, 15 to 21 per cent. of silica, about 7 per cent. of iron, about 2 per cent. of barium oxide, and a small proportion of arsenic. The reserves are estimated at about 1,500,000 tons.

Burma.—J. M. Campbell, *Tungsten Deposits of Burma and their Origin* (Economic Geology, 1920, vol. 15, pp. 511-534). The ore-bearing veins are rarely over 5 feet in width, generally less, but are very numerous. Most of the mines are small, generally not over 2000 feet in greatest dimension. Mining and recovery methods are crude, Chinese labour being used.

Canada.—*Mineral Resources of Canada* (Munitions Resources Commission, Canada, Final Report, 1920). This Commission was appointed for the purpose of instituting an inquiry respecting the supply and sufficiency of raw materials in Canada. The report includes the following papers: "Bauxite and the Possibility of its Occurrence in British Columbia," by W. F. Ferrier, pp. 15-39; "Chromite near Ashcroft, B.C.," by W. F. Ferrier, pp. 42-44; "Chromite in Quebec," by J. C. Gwillim, pp. 47-49; "Manganese in New Brunswick and Nova Scotia," by J. C. Gwillim, pp. 58-65; "Bog Manganese Deposits, Canaan River, New Brunswick," by W. L. Uglow, pp. 65-79; "Bog Manganese Deposits, Dawson Settlement, Albert County, N.B.," by W. L. Uglow, pp. 79-88; "Cowichan Manganese, Vancouver Island, B.C.," by G. C. Mackenzie, pp. 90-95; "Possibilities for Manufacturing Ferro-Manganese in Canada," by G. C. Mackenzie, pp. 96-103; "Molybdenite in Nova Scotia, Quebec, Ontario, and British Columbia," by J. C. Gwillim, pp. 108-133.

L. Reinecke, *Mineral Deposits between Lillooet and Prince George, British Columbia* (Canada Geological Survey, 1920, Memoir 118, pp. 96-96). An account is given of the chromite, molybdenite, manganese, and nickel deposits in this area.

China.—J. Coggin Brown, *The Mines and Mineral Resources of Yunnan* (Memoirs of the Geological Survey of India, 1920, vol. 47, Part I., pp. 1-201). In a general report on the mineral resources of the province of Yunnan in the south-west of China, an account is given of the mining and smelting of the iron ores which are widely distributed throughout the province. The smelting is carried on by primitive methods and, owing to the inaccessibility of the localities, it is not considered that there is any scope for the treatment of the iron ores by modern installations.

Dutch East Indies.—*Iron Industry for Celebes* (Journal of the Royal Society of Arts, October 8, 1920, vol. 68, p. 747). A survey on behalf of the Mining Department of the Government of Netherlands India shows that very extensive iron ore deposits exist in Celebes. Sufficient water-power could be developed to establish an industry in the island.

France.—L. Cayeux, *Siderite of the Iron Ores in the Basin of Longwy-Briey* (Comptes Rendus, 1920, vol. 170, pp. 1456-1458). The occurrence and probable origin of the siderite are discussed.

Hungary.—H. Quiring, *The Tertiary Manganese Ore Deposits near Kissoc, Hungary* (Zeitschrift für praktische Geologie, August 1920, vol. 28, pp. 117-123). The deposits occur on the north slopes of the Lower Tatra mountains. The manganese content is from 20 to 23 per cent. Working of the ores was actively pursued during the war.

Iceland.—*Iron Ore Deposits in Iceland* (Ironmonger, July 24, 1920, vol. 172, p. 105). The Dansk-Islandsk Anlaegs Selskab (Danish-Icelandic Installation Co.), of Copenhagen, has recently acquired concessions on the north-western peninsula of Iceland for the working of iron ore deposits and the utilisation of water-powers. The ore is brown ironstone, and the deposits extend throughout the peninsula, which is 12·4 miles long and 4·34 miles wide. The ore is found in a stratum of clay running almost horizontally at a height of 1000 feet above the base of the basalt rocks, the thickness of the vein being from 25 centimetres to 40 centimetres. The total quantity of ore is estimated at from 20,000,000 to 30,000,000 tons. Representative analyses show an iron content of 40 to 55 per cent. of iron.

Italy.—C. Crema, *The Bauxites of Istria and Dalmatia* (La Miniera Italiana, July-August 1920, vol. 4, pp. 3-10). The development of the bauxite industry in Istria and Dalmatia is described, with illustrations of the quarries and a map showing the occurrences of bauxite. The output of bauxite in 1917 was 163,122 tons, which was all exported to Germany and Switzerland.

Jugo-Slavia.—G. Gordon-Smith, *Mineral Wealth of the Kingdom of Jugo-Slavia* (Engineering and Mining Journal, October 9, 1920, vol. 110, pp. 705-712). An iron industry has not yet come into existence in Serbia, although the country is rich in iron ore. Investigations have been made only on a small scale, and it is impossible to judge the exact nature of the deposits. There is no doubt that a considerable amount of manganese ore exists in Serbia. One of the deposits of the Department of Kragujevats is known to yield ore containing up to 42 per cent. of manganese.

Letzous, *Mineral Resources of Jugo-Slavia* (France-Europe-Orientale : Iron and Coal Trades Review, October 1, 1920, vol. 101, p. 446). The iron ores found in Jugo-Slavia are magnetite, brown and red hæmatites, and oolitic ores. Brief particulars are given of the various deposits.

C. Hütter, *Chromite Occurrences in North Macedonia* (Zeitschrift für praktische Geologie, April 1920, vol. 28, pp. 53-59). Important chromite deposits, which have been worked on a small scale for many years, occur near Raduscha in Serbia, about 22 kilometres W.N.W. of Uskub. The ores consist of large chromiferous lumps, forming lenticular bodies in massive grey green serpentine rocks, which also contain chromite in the form of small grains. The origin and geological conditions of the deposits are discussed; and tables of analyses of the ore show the composition to range from 40·7 to 52·4 per cent. Cr_2O_3 , with 15 to 16 per cent. of ferric oxide. The deposits are capable of considerable development, and an aerial ropeway has been constructed to link up the mines with the railway system.

Morocco.—*Iron Ore in Morocco* (Parliamentary Paper, Cmd. 975 : Iron and Coal Trades Review, October 29, 1920, vol. 101, p. 586). In the occupied zone there are three iron ore mines about fifteen miles from Melilla. The most important is that of the Minas del Riff Company, where the ore averages about 63 per cent. of iron, 5 per cent. silica, and is low in phosphorus. The present output is about 15,000 tons a month. The ore worked by the Spanish Setolazar Company at the Navarrete mine is rather high in phosphorus and averages 57 to 58 per cent. of iron. The Spanish Alicantina Company is the least important of those working iron ore mines. The ore is of moderate quality and carries about 56 per cent. of iron. In addition to these mines there is a deposit of iron ore at Tres Forcas, close to the coast. The deposit appears to be of small extent, and the mineral consists largely of soft micaceous iron ore with about 43 per cent. of iron.

Newfoundland.—D. J. Davies, *Mineral Resources of Newfoundland* (Address before the Imperial Mineral Resources Bureau : Canadian Mining Journal, October 8, 1920, pp. 821-823). Notes are given on the extent, resources, and ownership of the Wabana iron ore deposits. Among other minerals the existence of which has been proved are manganese ores, chromite, molybdenite, coal, petroleum, and oil shale.

Peru.—J. J. Bravo, *Iron in Peru* (Engineering and Mining Journal, February 5, 1921, vol. 111, pp. 263-266). The development of the iron ore deposits is discussed, and particulars are given of the character of the Tambo Grande, Aija-Callaycancha, Huacravilca, and Marcona deposits.

Siberia.—*The Mineral Resources of Eastern Siberia* (L'Age de Fer, September 25, 1920, vol. 36, p. 590). The occurrences of iron, coal, petroleum, and the ores of precious and base metals are briefly referred to.

Coal and Iron in Eastern Siberia (Iron and Coal Trades Review, October 1, 1920, vol. 101, p. 442). Magnetite deposits are known, but have not been fully explored in the Amur Province; the basin of the Mamyn and the upper part of the Yvatikane are especially promising. The chief magnetite deposits are in the South Ussuri district. The best deposit now known is that of the Bielaya-Gora, which is estimated at 2,000,000 tons. Hæmatite is found in the Little Khingan mountains, the percentage of iron varying from 35 to 65 per cent. The Sergievsk deposits in the Ussuri district consists of magnetite and bog ore.

Spain.—H. Cole Estep, *Spain Mines Ore for Nine Nations* (Iron Trade Review, January 20, 1921, vol. 68, pp. 219–226). Brief particulars are given of the distribution of iron ore in Spain, together with tables showing the imports and exports of Spain during the past ten years.

P. H. Sampelayo, *Geological Conditions of the Bauxite Deposits in Catalonia* (Boletín del Instituto Geológico de España, vol. 41, 1920, pp. 1–147). A detailed study has been made by the author of the bauxite deposits south-west of Barcelona. The report is accompanied by a map, numerous photographs, and photomicrographs of specimens.

United States.—T. M. Broderick, *Economic Geology and Stratigraphy of the Gunflint Iron District, Minnesota* (Economic Geology, 1920, vol. 15, pp. 422–452). The general geology of the district is described, that of the Gunflint area in detail. Magnetite ore for concentration offers the only possibilities so far as is at present known. The formation runs about 25 per cent. iron and on concentration yields from 47 to 64 per cent. iron.

L. G. Westgate, *Deposits of Iron Ore near Stanford, Montana* (United States Geological Survey, 1920, Bulletin 715-F).

A. H. Hubbell, *The Replogle Iron Mine, near Wharton, N.J.* (Engineering and Mining Journal, October 2, 1920, vol. 110, pp. 658–664). Particulars are given of the operations of the Wharton Steel Company in opening up one of the numerous deposits of magnetite ore that occur in northern New Jersey. The ore is lean and high in silica, running about 36 per cent. of iron. It is concentrated, first by magnetic separators, the tailings then being treated in a wet mill on tables. The concentrates are being stored awaiting the completion of two new blast-furnaces.

S. E. Doak, *The Oriskany Iron Ores of Virginia* (Engineering and Mining Journal, February 26, 1921, vol. 111, pp. 386–387).

A. C. Gill, *Preliminary Report on the Chromite of Kenai Peninsula,*

Alaska (United States Geological Survey, 1919, Bulletin 712-D). The deposits at Claim Point and Red Mountain are described. The Claim Point ore contains from 28.6 to 46.8 per cent. of Cr_2O_3 , and samples of ore from Red Mountain gave on analysis 32.1 to 48.8 per cent. of Cr_2O_3 .

H. D. Miser, *Preliminary Report on the Deposits of Manganese Ore in the Batesville District, Arkansas* (United States Geological Survey, 1920, Bulletin 715-G). The average composition of the shipments made between 1917 and 1918 was about: Manganese, 47 per cent.; iron, 5.7 per cent.; phosphorus, 0.30 per cent.; silica, 7.0 per cent.; and alumina, 2.98 per cent.

J. T. Pardee and E. L. Jones, jun., *Deposits of Manganese Ore in Nevada* (United States Geological Survey, 1920, Bulletin 710-F). The classification and general features of the deposits which are widely distributed in Nevada are described.

E. L. Jones, jun., *A Deposit of Manganese Ore in Wyoming* (United States Geological Survey, 1920, Bulletin 715-C).

E. L. Jones, jun., *Some Deposits of Manganese Ore in Colorado* (United States Geological Survey, 1920, Bulletin, 715-D).

E. S. Larsen and C. S. Ross, *The R. and D. Molybdenum Mine, Taos County, New Mexico* (Economic Geology, 1920, vol. 15, pp. 567-573). The geology of the district is described. The ore exposed is of good grade and uniform.

R. M. Overbeck, *Nickel Deposits in the Lower Copper River Valley, Alaska* (United States Geological Survey, 1919, Bulletin 712-C).

Mineral Resources of the World.—F. H. Hatch, *The Iron Ore Supplies of the World* (Geological Magazine, 1920, vol. 57, pp. 504-517). The iron ore reserves of the United Kingdom, the United States, Cuba, Newfoundland, Brazil, Scandinavia, central Europe, Spain, and northern Africa total 30,300 million tons. Another 1500 million tons should be added for the small deposits of Russia, Austria, Greece, Chili, Venezuela, Mexico, and Canada. The resources of Africa, Asia, and Australia are unknown, but may be theoretically estimated at 52,200 million tons.

W. G. Rumbold, *Chromium Ore* (Imperial Institute: Monographs on Mineral Resources, 1921, pp. 1-58). The occurrences, character, and uses of chromium ore are described.

B. Simmersbach, *Recent Developments in the Treatment and Uses of Molybdenum* (Zeitschrift für praktische Geologie, March-April 1920, vol. 28, pp. 47-51, 59-69). A general review of the occurrences, exploitation, and concentration of molybdenum ores, with notes on the manufacture of ferro-molybdenum and the use of molybdenum as an alloy with steel and other metals.

A. H. Hunter, *Molybdenum* (Paper read before the American Iron and Steel Institute, May 27, 1921). The paper deals with the occurrences, properties, and uses of molybdenum.

II.—MINING OF ORES.

Methods of Mining.—*Marion Steam Shovel* (Iron and Coal Trades Review, December 24, 1920, vol. 101, p. 869). Illustrated particulars are given of the operation of Marion steam shovels for stripping the face at the mines of the Oxfordshire Ironstone Company at Banbury.

Iron Ore Handling.—H. J. Smith, *Electrical Grab Transporters for Han-Yeh-Ping* (Electrician, December 31, 1920, vol. 86, pp. 14-17). The iron ore mines belonging to the Han-Yeh-Ping Iron and Coal Corporation are worked on the open-cast system, and transported to the works at Han-Yeh by railway. New ironworks are being built at Ton Tsu-Pao. The conditions on the river Yangtse, upon which the ore, limestones, coal, and coke are borne to the works are such, and the tidal falls so great (over 45 feet), that cantilevers of great size and weight have had to be installed for the handling of two 11-ton grabs. Illustrations of the plant are given. The greatest depth to which a grab has to be lowered in practice is 75 feet at low water. The ore is emptied from the lighters and deposited in a system of bunkers each holding 1000 tons. At the Ton-Tsu-Pao Works there will eventually be eight 450-ton blast-furnaces, the first two of which are in course of erection.

III.—PREPARATION OF ORES.

Microscopic Examination of Iron Ore.—H. Schneiderhöhn, *The Microscopic Examination of Iron Ores with Special Reference to its Bearing on Ore-dressing Processes* (Stahl und Eisen, October 14, 1920, vol. 40, pp. 1361-1365). The author advocates the systematic microscopic examination of iron-bearing minerals as an aid in determining their treatment for concentration by magnetic methods and wet concentration processes.

Sintering of Ore.—W. E. Greenawalt, *The Greenawalt Sintering Process* (Mining and Scientific Press, January 15, 1921, vol. 122, pp. 81-85). This process is intermittent in operation, a charge being subjected to a down draft blast of air, and after ignition the sintering action proceeds from the top downwards.

REFRACTORY MATERIALS.

Magnesite.—W. Petrascheck, *The Magnesites of California and Nevada* (Montanistische Rundschau, August 16, 1920, vol. 12, pp. 344–345). The deposits, reported on by Gale in 1914 (U.S. Geological Survey, 1914, Bulletin No. 540), yield a product much inferior to the Austrian magnesites. Later reports confirm this view.

Fireclay.—W. Mathias, *The Clay and Loam Deposit at Hettenleidsheim, in the Palatinate* (Zeitschrift für praktische Geologie, September 1920, pp. 133–144). The chemical composition of the clays and loam is stated, and the origin, geological conditions, and petrography of the strata are discussed.

Properties, Tests, and Uses of Refractories.—P. Gilard, *Silica Bricks* (Revue Universelle des Mines, March 15, 1921, vol. 8, pp. 548–565). A review of the work performed by the Commission des Produits Céramiques et Réfractaires during the war in the study of the properties of the raw materials and the manufacture and testing of silica brick.

K. Endell, *Behaviour of Refractory Bricks under Load at High Temperatures* (Stahl und Eisen, January 6, 1921, vol. 41, pp. 6–9). Cylindrical specimens of refractory bricks were tested under pressure in a lever press combined with a small electric heating furnace, capable of heating up the specimens while under pressure to 1800° C. Under a pressure of 1 kilogramme per cm.², firebrick specimens softened at 1300° and were compressed three-fifths of their height at 1500°. Magnesite specimens softened at about 1500° and were compressed one-fifth of their height at 1650°. Silica specimens softened at about 1650° and broke at 1680°. Carbon specimens were heated to 1720° without softening.

R. M. Howe, *Vital Factors in the Testing of Fireclay Refractories and in the Interpretation of the Results* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part I. pp. 278–290). The results of laboratory tests of refractories do not always agree with those obtained with the same material in actual service, and it would appear desirable to develop more reliable tests or to modify present ones. A careful study of the results of load tests, fusion tests, spalling tests, slag tests, and reheating tests shows that durability in service depends as much upon the nature of the raw material as on the structure of the product.

V. Bodin, *Strength of Refractories at Different Temperatures* (Céramique, 1920, vol. 23, pp. 177-184). It was found that for fireclay, bauxite, corundum, carborundum, silica, and zirconia refractories the crushing strength decreases with an increase in temperature up to about 800°. Above this temperature the strength increases rapidly with an increase of temperature until about 1000° is reached, after which the strength again decreases with an increase in temperature. With magnesite and chrome refractories the strength decreases with an increase of temperature showing no increase in strength at 1000°.

M. W. Travers, *Note on the Tensile Strength of Refractory Materials* (Journal of the Society of Glass Technology, August 1920, vol. 4, pp. 138-139). In many places in furnace construction, and especially in pot furnace walls, tension and hot compression is the important property. The theory that an ideal refractory should consist of a very high percentage of infusible material, carefully graded and bonded with a very small quantity of vitreous bond, may be justified from the standpoint of resistance to load, but it does not follow that tensile stresses will be equally well withstood.

A. S. Watts, *A Possible Explanation of Failure under Load at High Temperatures as Displayed by Fireclay Refractories* (Journal of the American Ceramic Society, 1920, vol. 3, pp. 448-459).

W. J. Rees, *Refractories for Electric Furnaces* (Paper read before the Sheffield Society of Metallurgists: Foundry Trade Journal, January 20, 1921, vol. 23, pp. 66-67). The author discusses the most satisfactory materials for use in the construction of electric furnaces, and considers certain fundamental data relative to the physical and chemical properties of the available materials.

W. J. Rees, *Refractories for the Iron and Steel Industries* (Paper read before the Staffordshire Iron and Steel Institute, January 22, 1921).

R. M. Howe, *Linings for Electric Furnaces* (Paper read before the Electric Furnace Association, Milwaukee, October 6, 1920; Iron Trade Review, December 2, 1920, vol. 67, pp. 1541-1543). The author discusses the physical characteristics of the nine raw materials now most commonly used in the manufacture of electric furnace linings, namely, fireclay, silica (or ganister), magnesite, dolomite, chromite, bauxite (and diaspore), zirconite, carborundum, and alundum.

A. F. Greaves-Walker, *Electric Furnace Refractories* (Paper read before the Electric Furnace Association, October 7, 1920: Chemical and Metallurgical Engineering, November 10, 1920, vol. 23, pp. 933-936). A brief description of the raw materials, together with a list of recommended refractories used in melting the different metals.

Refractories for Electric Furnaces (Iron and Coal Trades Review, November 5, 1920, vol. 101, p. 616). In a discussion on the above subject recently held by the Electric Furnace Association in Columbus, Ohio, a contribution from the Foote Mineral Company outlined the requirements of electric furnace refractories, and the use of carborundum as a refractory was dealt with by M. L. Hartmann.

H. F. Staley, *Development of Refractories* (Chemical and Metallurgical Engineering, December 15, 1920, vol. 23, pp. 1167-1171). The author reviews the progress in refractory research and the improvements in refractory products due to increased knowledge.

Manufacture of Crucibles.—A. V. Bleining, *Properties of American Bond Clays and their Use in Graphite Crucibles and Glass Pots* (United States Bureau of Standards, 1920, Technologic Paper 144).

G. D. Dub and F. G. Moses, *Mining and Preparing Graphite for Crucible Use* (United States Bureau of Mines, 1920, Bulletin 112). The methods of mining graphite and experiments on concentration and milling are described.

Refractory Mortars.—R. M. Howe, *Refractory Mortars* (Chemical and Metallurgical Engineering, August 11, 1920, vol. 23, pp. 232-234). In making refractory mortars it is usual to add to the ground fireclay such materials as ground silica and alumina, which improve the general properties of plastic clay. Portland cement, lime, salt, and water-glass if added to the clay will lower the point of fusion.

Definition of the Term "Ceramics."—*Report of the Committee on Definition of the Term "Ceramics"* (Journal of the American Ceramic Society, 1920, vol. 3, pp. 526-536). The term "ceramics" should include claywares, cementing materials, glasses of all kinds, enamelled metal products, refractories, abrasives, and various electric and thermal insulating materials.

W. A. Oldfather, *Note on the Etymology of the Word Ceramics* (Journal of the American Ceramic Society, 1920, vol. 3, pp. 537-542).

FUEL.

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I.—CALORIFIC VALUE.

Value of Coal for Gas Manufacture.—R. Mezger and M. Müller, *Determination of the Calorific Value of the Volatile Constituents of Coal as a Measure of its Suitability for Gas Manufacture* (Journal für Gasbeleuchtung, 1920, vol. 63, pp. 669–673).

Surface Combustion.—O. Essich, *The Further Development of Surface Combustion* (Stahl und Eisen, February 17, 1921, vol. 41, pp. 228–232). The principles of surface combustion are explained and improved methods for its application are illustrated and described.

Fuel Economy.—Sir Dugald Clerk, *Coal Conservation* (Paper read before the British Commercial Gas Association: Iron and Coal Trades Review, October 31, 1919, vol. 99, pp. 562–563). The question of coal conservation is discussed, special reference being made to the relative efficiencies of gas and electricity.

Sir Arthur Duckham, *Coal as a Future Source of Oil Fuel Supply* (Journal of the Institution of Petroleum Technologists, January 1921, vol. 7, pp. 3–26). The author is of opinion that the industrial future of this country lies in the conversion of coal at the mouth of the mine into liquid and gaseous fuels and their transport through pipe-lines to the consumer. He discusses the various processes of coal carbonisation. The ideal system would be the complete gasification of coal, preferably by the single stage process, with the recovery of the maximum amount of gas and liquid fuel with a minimum of cracking. The gas should be stripped of all saturated hydrocarbons and the maximum amount of nitrogen recovered.

J. R. L. Allott, *Conservation of Fuel and By-Product Manufacture* (Presidential Address before the North Staffordshire Institute of Mining Engineers: Iron and Coal Trades Review, November 26, 1920, vol. 101, pp. 729).

M. Sklovsky, *Fuel and Combustion* (Paper read before the American Foundrymen's Association, October 1920). The need of fuel economy is emphasised, and the possible saving of fuel in the melting of metals and annealing operations is pointed out.

A Symposium on Fuel Economy was held in New York on September 21, 1920 (Chemical and Metallurgical Engineering, October 6, 1920, vol. 23, pp. 658-660). Abstracts are given of the following papers: "Burning Coal at 100 per cent. B.T.U. Efficiency," by W. O. Renkin; "Saving Fuel by Controlling Chimney Losses," by F. F. Uehling; "Reducing Conduction and Radiation Heat Losses," by S. L. Barnes; "Increasing Conduction and Reducing Fuel Consumption," by W. R. Van Northwick; "Fluid Heat Transmission," by A. B. McKechnie; "The Reason for the Fuel Saving in the Dressler Kiln," by C. Dressler.

Fuel and its Conservation (Mechanical Engineering, January 1921, vol. 43, pp. 22-31). A general discussion on fuel economy, based on the following papers: "Fuel Supply of the World," by L. P. Breckenridge; "Distillation of Fuels as Applied to Coals and Lignites," by O. P. Hood; "Fuel Conservation," by D. M. Myers; "Form Value of Energy in Relation to its Production, Transportation, and Application," by C. G. Gilbert and J. E. Pogue.

Pulverised Coal.—C. F. Herington, *Metallurgical Use of Pulverised Fuel* (Iron Age, April 14, 1921, vol. 107, pp. 965-967). The author discusses the advances made in the utilisation of pulverised fuel in metallurgical furnaces, and gives a list of the plants operating on this fuel in the United States.

J. F. Shadgen, *Industrial Application of Powdered Fuel* (Iron Age, March 31, 1921, vol. 107, pp. 839-842). The method of transfer of heat energy, the temperature cycles involved, the design of combustion chambers, and the applications of powdered fuel are discussed.

Burning Powdered Coal (Iron Age, December 16, 1920, vol. 106, pp. 1614-1615). An illustrated description of the Grindle system of conveying and burning powdered coal.

H. D. Savage, *Use of Powdered Fuel under Steam Boilers* (Paper read before the American Iron and Steel Institute, May 27, 1921). A description of the plant in use for grinding fuel with details of operating costs.

H. D. Savage, *Powdered Fuel for Central Station Boilers* (Electric News, Toronto, 1920, vol. 29, pp. 31-33). The author reviews the results obtained with the Lopulco system of burning pulverised coals.

H. Drouot, *The Industrial Use of Pulverised Fuels* (Technique Moderne, 1920, vol. 12, pp. 407-417, 476-479). The author reviews

the merits of pulverised coal, the various systems of handling and feeding it, and the various applications.

Purchase of Fuel on a Heat Unit Basis.—W. H. McMillan, *Purchase of Coal on a Scientific Basis* (Paper read before the National Association of Colliery Managers: Iron and Coal Trades Review, November 12, 1920, vol. 101, p. 641).

R. Lessing, *Distribution of Mineral Matter in Coal* (Transactions of the Institution of Mining Engineers, February 1921, vol. 60, pp. 288-309). The results of an investigation are put forward in order to prove the insufficiency of information obtainable from the customary ash test performed in ordinary coal analysis. No trustworthy opinion of the intrinsic value of coal can be formed without due consideration being given to the character of its ingredients and the ratio to each other in which they occur.

Fuel for Central Heating.—H. Kreisinger, *By-Product Coke, Anthracite, and Pittsburgh Coal as Fuel for Heating Houses* (Journal of Industrial and Engineering Chemistry, January 1921, vol. 13, pp. 31-33). Results of tests in heating boilers for central heating of houses, with coke, anthracite, and Pittsburgh coal, show that the efficiency obtained with coke is a little better than with anthracite and 10 to 17 per cent. better than with coal. The percentage of refuse is higher.

II.—COAL.

British Empire.—J. H. Ronaldson, *Coal* (Imperial Institute: Monographs on Mineral Resources, 1920, pp. 1-166). The history, growth, and output of the coal industry, with special reference to the British Empire, are described.

England.—H. A. Baker, *Structural Features of the East Kent Coalfield* (Iron and Coal Trades Review, December 10, 1920, vol. 101, pp. 785-788). The author outlines present day knowledge of the structure of this coalfield.

H. H. Ridsdale, *The Geological Relationship of the South Staffordshire, Warwickshire, South Derbyshire, and Leicestershire Coalfields* (Transactions of the Institution of Mining Engineers, January 1921, vol. 60, pp. 190-205).

Ireland.—G. A. J. Cole, *Reserves in the Irish Coalfields* (Appendix to the Report of the Irish Coal Industry Committee: Iron and Coal Trades Review, March 4, 1921, vol. 102, p. 314). The total estimate of the Irish reserves is 221,965,000 tons.

Asia Minor.—A. Roccati, *The Coal Basin of Heraclea* (La Miniera Italiana, July–August 1920, vol. 4, pp. 10–17). A description of the coal region of Heraclea, with illustrations of the mines and workings, and notes on the quantity of coal.

Austria.—L. Waagen, *Coal Ownership and Coal Requirements in German Austria* (Zeitschrift des Oesterr. Ingenieur- und Architekten Vereines, October 1, 1920, vol. 72, pp. 249–252). With the exception of an insignificant quantity of bituminous coal and anthracite in the Alpine regions, the only available coal resources in Austria consist of lignite, estimated to amount to $308\frac{1}{2}$ million tons, with another 30 millions in Western Hungary. The average yearly production is $2\frac{1}{2}$ millions tons, which falls far short of the requirements of the country, which are estimated at 7·8 million tons of hard coal and 7·3 million tons of lignite.

Belgium, France, Germany.—H. F. Crooks, *Notes on the Coal Industry of North-Eastern France, Belgium, the Saar, and Westphalia, 1904–1913* (Economic Geology, 1920, vol. 15, pp. 277–311). The geological formation and distribution of the coals of each area is discussed, and much data is given concerning the character, output, costs, chemical composition, thermal values, coking qualities, and reserves of each district.

China.—J. Coggin Brown, *The Mines and Mineral Resources of Yunnan* (Memoirs of the Geological Survey of India, 1920, vol. 47, Part I., pp. 1–201). There is a great abundance of coal in the province of Yunnan, but no accurate surveys have yet been made. Mining operations are carried out by the Chinese by the most primitive methods, and in many places the coal yields an excellent coke. But owing to the landlocked position of the province the coal is not likely to find a sale except in the local market.

E. Schultze, *Coal Resources of China* (Zeitschrift für praktische Geologie, June–July 1920, vol. 28, pp. 93–97, 108–111). The total coal resources of China are estimated by some authorities at 1,300,000 million tons, the principal deposits occurring in the provinces of Schansi, Yunnan, and Hunan. The present coal-mining developments are reviewed.

Germany.—P. Kukuk, *Remarkable Peculiarities of the Cannel Coal Seam of the Lippe Basin* (Glückauf, October 9, 16, 1920, vol. 56, pp. 805–810, 829–835). At Lohberg Colliery a seam of cannel coal mixed with carbonate of iron is being worked. The ironstone contains 43·87 per cent. of ferric oxide, 1·05 per cent. of manganic oxide, and 0·78 per cent. of phosphoric acid. The mineral finds its best application in the mixed gas producer.

Holland.—C. Lemaire, *Iron and Coal in Holland* (L'Age de Fer, October 25, 1920, vol. 36, pp. 662-664). A review of the coal resources and coal industry of Holland is presented

Italy.—R. Masini, *Investigation of the Anthracite and Graphite of Mount Pisano, Lucca* (Rassegna Mineraria, February 1920, vol. 52, pp. 26-27).

G. Castelli, *The Lignite Mines of Gualo Cattaneo* (Rassegna Mineraria, February 1920, vol. 52, pp. 28-29).

D. Meneghini, *Some Lignites of the Venetian Lower Alps* (Giornale di chimica industriale ed applicata, April 1920, vol. 2, pp. 169-171).

Jugo-Slavia.—G. Gordon-Smith, *Mineral Wealth of the Kingdom of Jugo-Slavia* (Engineering and Mining Journal, October 9, 1920, vol. 110, pp. 705-712). Particulars are given of the coal deposits of Serbia.

Peru.—W. Campbell, *Coal Veins of Peru* (Transactions of the Institution of Mining Engineers, November 1920, vol. 60, pp. 51-55). The coal-veins are of two distinct series and are about twenty miles apart. The first of the series is near Huari and the second at Yauli. In the latter series coal is being mined at Rumichaca. A mixture of Rumichaca and Huari coals is used for making blast-furnace coke.

Siberia.—*Coal and Iron in Eastern Siberia* (Iron and Coal Trades Review, October 1, 1920, vol. 101, p. 442). Brief particulars are given of the coal deposits in this district.

South Africa.—F. A. Steart, *Notes on the Geology of the North-Western Portion of the Natal Coalfield* (Paper read before the Geological Society of South Africa: Iron and Coal Trades Review, October 1, 1920, p. 449). Although the Coal Measures cover a large area, the value of the coalfield is considerably lessened by the small number of coal-seams it contains in comparison with the number in many coalfields in Europe.

Spitsbergen.—H. M. Cadell, *Coal-Mining in Spitsbergen* (Transactions of the Institution of Mining Engineers, January 1921, vol. 60, pp. 119-142). The general geological structure of the coal area is described, and particulars are given of the mines of the Longyear Colliery.

United States.—G. W. Evans, *Alaskan Coalfields* (Paper read before the American Institute of Mining and Mechanical Engineers, February 1921). The author describes briefly the four principal coalfields—the Nenana, the Matanuska, the Kachemak Bay, and the Bering River.

G. R. Mansfield, *Coal in Eastern Idaho* (United States Geological Survey, 1920, Bulletin 716-F).

G. H. Ashley and C. R. Fettke, *Pennsylvania Coals and Shales greatly Vary in their Content of Oil* (Coal Age, March 3, 1921, vol. 19, pp. 401-403). The results are given of a series of experiments made to determine the amount of oil obtainable from Pennsylvania coals and black shales. For purposes of comparison the results of similar tests made on the cannel coals and rich oil shales of other States are also given.

G. H. Ashley, *Abram Creek—Stony River Coalfield of North-Eastern West Virginia* (United States Geological Survey, 1920, Bulletin 711-F, pp. 85-103). This field contains a large deposit of semi-bituminous smokeless coal. Analyses of ten samples gave, ash 5 to 16 per cent., and sulphur 0.5 to 3.5 per cent. The heating value averaged 13,100 B.Th.U.

Formation of Coal.—J. E. Hackford, *Nature of Coal* (Paper before American Institute of Mining and Metallurgical Engineers, September 1920 : Coal Age, September 16, 1920, vol. 18, pp. 582-584). A theory is put forward concerning the mode of formation and nature of coal, which is compared with the mode of formation of oil.

Constituents of Coal.—F. S. Sinnatt, A. Grounds, and F. Bayley, *The Inorganic Constituents of Coal with Special Reference to Lancashire Seams* (Journal of Society of Chemical Industry, January 15, 1921, vol. 40, pp. 1-3-T). The paper describes a study of the white inorganic partings, termed ankerites, which occur in most coal-seams, generally at right angles to the bedding plane.

Microstructure of Coal.—R. Thiessen, *Recent Developments in the Microscopic Study of Coal* (Canadian Mining Journal, January 28, February 4, 11, 18, 1921, vol. 42, pp. 64-68, 86-91, 109-113, 124-128). The article describes the results and advantages obtained from the knowledge gained by the microscopic study of coal.

Swelling Coals.—F. Schreiber, *Swelling Coals and a Method for Determining the Amount of Swelling* (Stahl und Eisen, September 23, 1920, vol. 40, pp. 1278-1279).

Properties of Coal.—G. Charpy and J. Durand, *The Melting Point of Coal* (Comptes Rendus, December 27, 1920, vol. 171, pp. 1358-1360). An investigation has been made to determine the temperature at which certain coals fuse, that being the point at which agglomeration begins to take place in the coking process. The point of fusion was found to be independent of the percentage of volatile matter and varies for different coals within very wide limits. The fusibility of a coal
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and its suitability for coking are allied to its state of oxidation. Coal oxidised by heating to 120°C . is no longer capable of fusing.

M. Godchot, *Oxidation of Coal* (Comptes Rendus, 1920, vol. 171, pp. 32-34).

H. J. Hailstone, *Determination of the Specific Gravity of Coal and its Products* (Gas Journal, 1920, vol. 151, pp. 566). The specific gravity of small coal or pitch can be determined by flotation, using a solution of sodium thiosulphate of specific gravity 1.350.

Charcoal.—L. Tissier, *Carbonisation of Wood by the Exhaust Gases of Motors* (Chimie et Industrie, February 1921, vol. 5, pp. 136-142). The exhaust gases of motors generally have a temperature of 400° to 450°C ., and their composition is approximately: Nitrogen, 78 per cent.; carbon dioxide, 14 per cent.; oxygen, 8 per cent. They are therefore not combustible. By leading them through wood piled properly in a special chamber, the wood is brought to a temperature of 250° and will distil, without smouldering or flaming, being constantly immersed in a neutral gas. Excellent charcoal is obtained, with recovery of all the valuable by-products.

Peat.—*Utility of Irish Peat Deposits* (Iron and Coal Trades Review, April 22, 1921, vol. 102, p. 560). An abstract of the suggestions and recommendations made in a Report submitted to the Fuel Research Board by a Committee appointed to inquire into the winning, preparation, and utilisation of Irish peat for fuel and domestic purposes.

III.—COKE.

Coking Coals.—*Chemical and Physical Classification of Coal* (Gas World (Coking and By-Products Section), 1920, vol. 73, pp. 13-14). A comparison of the classification of Gruner, Seyler, and Field and Fraser for the purpose of defining the best coking coal.

T. Gray and J. G. King, *Assay of Coal for Carbonisation Purposes* (Department of Scientific and Industrial Research, Technical Paper No. 1: Iron and Coal Trades Review, March 11, 1921, vol. 102, p. 362). Details are given of the experimental work carried out in connection with the elaboration of a method of coal assay, the object being to ascertain by direct weighing and measurement the yields of gas, oil, water, and carbonaceous residue resulting from the carbonisation of coal at different temperatures.

Moisture in Coal and Coke.—A. H. Thwaite, *Effect of Excessive Moisture in Coal* (Gas World, 1920 (Coking and By-Products Section), No. 1863, pp. 10-11). The moisture content of coal for coking should run about 8 to 10 per cent. Washed coal can be drained to better

advantage by crushing the large lumps of good coal separately from the poor coal to 2-inch cubes or smaller before mixing. For each 1 per cent. of water above 8 per cent. in a charge, 924 cubic feet of gas are required to evaporate it.

G. Deladrière, *The Value of Metallurgical Coke* (Revue Universelle des Mines, April 15, 1921, vol. 9, pp. 93-107). A study of the relative value of coke containing different proportions of moisture and ash when used in the blast-furnace.

Hardness of Coke.—O. R. Rice, *Importance of Hardness of Blast-Furnace Coke* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921). The conditions affecting the hardness of coke are discussed and an apparatus to determine hardness is described. This is a combination tumbler and ball mill.

C. J. Rice, *Standardising the Testing of Coke* (Iron Trade Review, April 14, 1921, vol. 68, pp. 1037-1038). A description is given of a method of testing the hardness of coke, recommended by the Southern Ohio Pig Iron Association. A tumbling barrel similar to that used for cleaning castings is used in the test.

Sulphur in the Coking Process.—A. R. Powell, *A Study of the Reactions of Coal Sulphur in the Coking Process* (Journal of Industrial and Engineering Chemistry, November 1920, vol. 12, pp. 1069-1077). Sulphur exists in coal in three typical forms: pyrite or marcasite, sulphates, and organic sulphur. The changes which these forms undergo during coking have been studied and five classes of reactions have been established.

A. R. Powell, *The Desulphurising Action of Hydrogen on Coke* (*Ibid.*, pp. 1077-1081). The effect of hydrogen in removing sulphur from coke is very marked, the greater part being removed within three hours at a temperature of 1000° C. The character of the coke is not otherwise affected by the passage of hydrogen.

A. R. Powell, *Some Factors affecting the Sulphur Content of Coke and Gas in the Carbonisation of Coal* (Journal of Industrial and Engineering Chemistry, January 1921, vol. 13, pp. 33-35). The fact that hydrogen has a highly desulphurising effect on coke points to the possibility of making practical application of this principle to the desulphurisation of the coking mass in coke-ovens.

Coking Practice.—A. Thau, *European and American Coking Practice Compared* (Stahl und Eisen, November 25, December 2, 1920, vol. 40, pp. 1603-1606). The various factors influencing the coking process as carried out in Europe and America are reviewed, and the author replies to criticisms made by J. I. Thompson (Proceedings of the Engineers' Society of Western Pennsylvania, 1920, vol. 35, pp. 427-448) as the result of a visit to a number of continental coking plants.

The shorter coking time in America is mainly due to the use of silica brick for the chamber construction which enables working at higher temperatures, and to the good quality of the coking coal. While in charge of an installation in Sweden the author experienced a change from British coal to American coal for use in the coke-ovens, and found that a coke from American coal was superior in hardness and density and the coking time fell from twenty-nine to twenty hours.

Baille-Barrelle, *The Coking of the Saar Coals* (Revue de l'Industrie Minérale, Mémoires, February 15, 1921, pp. 221-240). Nine coke-oven plants are in existence in the Saar district. The yield of coke from Saar coal is about 67 per cent.; on account of its friability the proportion of breeze and fines is often 7 to 8 per cent.

E. H. Bauer, *Making Foundry By-Product Coke* (Foundry, 1920, vol. 48, pp. 509-516).

R. S. McBride and W. A. Selvig, *Coking of Illinois Coal in Koppers Type Ovens* (United States Bureau of Standards, 1919, Technologic Paper 137). A description of a test carried out at the works of the Minnesota By-Products Coke Company.

A. Thau, *Mechanical Coke-quenching and Coke-handling Appliances* (Glückauf, July 24, 31, August 7, 1920, vol. 56, pp. 585-590, 608-611, 629-633). A description of modern installations for coke quenching and handling.

Corrosion of Coke-Ovens.—A. E. Findley, *Corrosion of Coke-Oven Walls* (Journal of the Society of Chemical Industry, January 31, 1921, vol. 40, pp. 7-8-T). It is shown that salt and iron are the most injurious ingredients in coking slack for producing corrosion of the coke-oven walls. As the proportion of salt increases the durability of the walls decreases, and if both salt and iron are present it is still further diminished. Iron and moisture, even if present in relatively large amounts, do not appreciably affect the durability if the salt is very low.

By-Product Recovery.—A. Thau, *By-Product Industry Progresses* (Iron Trade Review, March 10, 1921, vol. 68, pp. 695-697, 703-704). The author deals with the improvements in the design of by-product coke-ovens during the last forty years, and compares various types and subsidiary equipment.

A. Thau, *The New Benzol Plant at the Coke-Ovens of the Oxelösund Ironworks* (Glückauf, January 1, 8, 1921, vol. 57, pp. 4-11, 25-31). A description of a benzol recovery plant of a new type recently installed in Sweden.

A. Thau, *Removing Tar from Coke Gas* (Iron Trade Review, November 11, December 9, 1920, vol. 67, pp. 1331-1335, 1607-1610). The rotary tar extractor, although designed for treating blast-furnace

gas, now finds wide use in coke-oven practice. Various types of rotary extractors are described and illustrated.

M. E. Nicklin, *Manufacture of Sulphate of Ammonia* (Paper read before the Coke-Oven Managers' Association, January 25, 1921: Iron and Coal Trades Review, February 4, 1921, vol. 102, p. 160). The advantages and disadvantages of the indirect, semi-direct, and direct processes are discussed.

S. R. Bellamy, *Semet-Solvay Direct Sulphate Process* (Paper read before the American Institute of Chemical Engineers: Colliery Guardian, November 12, 1920, vol. 120, p. 1397). The recovery of ammonia at the by-product coke-oven plant of the Ford Motor Co., River Rouge, Michigan, is described.

C. F. Tidman, *Alcohol from Coke-Oven Gas* (Paper read before the Cleveland Institution of Engineers, March 7, 1921: Iron and Coal Trades Review, March 11, 1921, vol. 102, p. 350).

B. R. Tunison, *Science and Industrial Alcohol* (Chemical and Metallurgical Engineering, September 8, 1920, vol. 23, pp. 474-480). Various proposals for the manufacture of pure alcohol, including its extraction from blast-furnace and coke-oven waste gases, are dealt with, and the future prospects of the problem discussed.

F. W. Sperr, jun., and E. H. Bird, *By-Product Coking* (Journal of Industrial and Engineering Chemistry, January 1921, vol. 13, pp. 26-31). A general review of the advantages and economies secured by recovery of by-products.

F. W. Sperr, jun., *Coke and By-Products as Fuels for Metals Melting* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1920). The fuel value of coke and by-products is discussed.

Low Temperature Carbonisation of Coal and Recovery of Primary Tar.—*Furnace for Low Temperature Carbonisation of Coal* (Iron and Coal Trades Review, October 1, 1920, vol. 101, p. 449). A description is given of the Harris retort or furnace. In most essentials it is practically the same as that previously used for the mechanical roasting of pyrites. Very slight modifications were needed to adapt it for the carbonisation of coal. A gas main has been provided in each chamber to tap off the vapours at the temperatures at which they are given off, and thus prevent their partial destruction by passing them through the hotter chambers to a common outlet. The retort is designed to carbonise about 10 cwts. per hour, and requires about 2 b.h.p. to drive it.

H. L. Armstrong, *Recent Advances in Low Temperature Carbonisation* (Journal of the West of Scotland Iron and Steel Institute, November 1920, vol. 28, pp. 10-24). The value of the low temperature process in comparison with the high temperature process is discussed, and figures are given which show that the low temperature process gives considerably better economic results.

H. L. Armstrong, *Low Temperature Carbonisation* (Paper read

before the Coke-Oven Managers' Association, December 16, 1920: Iron and Coal Trades Review, December 24, 1920, vol. 101, p. 873). Particulars are given of the plant of the Low Temperature Carbonisation, Ltd., at Barnsley.

H. E. Armstrong, *Relativity and the Problems of Coal. Low Temperature Carbonisation and Smokeless Fuel* (Journal of the Royal Society of Arts, May 6, 1921, vol. 69, pp. 385-407). An account is given of the recent experiments at Barnsley on low temperature carbonisation.

F. Foerster, *Low Temperature Distillation of Coal* (Journal für Gasbeleuchtung, September 25, 1920, pp. 621-628). An investigation of tars is described, with results of experiments in the recovery of primary tar, and notes on the practical operation of the low temperature distilling process.

G. H. Thurston, *Low and High Temperature Carbonisation* (Journal of the Society of Chemical Industry, March 15, 1921, vol. 40, pp. 51-56-T). The Smith continuous system of carbonisation is described. Two plants are in operation in the United States.

O. Monnett, *Low Temperature Coking of Utah Coals* (Chemical and Metallurgical Engineering, December 29, 1920, vol. 23, pp. 1246-1249). A summarised description of laboratory investigations carried out by the United States Bureau of Mines to determine the coking properties of a series of Utah coals. The apparatus used is described and the results of the tests are tabulated.

H. A. Curtis, *Low Temperature Carbonisation of Coal and Manufacture of Smokeless Fuel Briquettes* (Chemical and Metallurgical Engineering, September 8, 1920, vol. 23, pp. 499-501). The nature and yield of the products obtained respectively by low temperature and high temperature carbonisation of coal are described, with special reference to the carbo-coal process for producing an anthracite-like fuel from bituminous coal. This process is in operation at the Experimental Plant at Irvington, New Jersey, which has a capacity of 100 tons of coal per day, and also at Clinchfield, Virginia, where a 500-ton plant is in operation. The results of the process and the mode of briquetting the residues are dealt with.

At the sixtieth meeting of the American Chemical Society, the following papers on fuel were presented:

S. W. Parr and T. E. Layng, *Low Temperature Carbonisation and its Application to High Oxygen Coals* (Journal of Industrial and Engineering Chemistry, January 1921, vol. 13, pp. 14-17).

E. Stansfield, *Carbonisation of Canadian Lignite* (*Ibid.*, pp. 17-23).

H. A. Curtis, *The Commercial Realisation of the Low Temperature Carbonisation of Coal* (*Ibid.*, pp. 23-26).

H. F. Yancey and T. Fraser, *Distribution of the Forms of Sulphur in the Coal-Bed* (*Ibid.*, pp. 35-37).

H. C. Porter, *Fuel Conservation, Present and Future* (*Ibid.*, pp. 47-51).

IV.—LIQUID FUEL.

England.—*Norfolk Oilfields* (Colliery Guardian, October 22, 1920, vol. 120, pp. 1157–1158). Particulars are given from the report of the English Oil Fields, Ltd., of the chemical composition and oil content of the shale deposits in Norfolk.

Scotland.—M. J. Gavin, *The Necessity for Research in the Oil-Shale Industry* (Chemical and Metallurgical Engineering, September 8, 1920, vol. 23, pp. 489–495). An account of the shale oil industry of Scotland and of the plant and practice employed in the production of refined products from Scottish shale, with deductions for the guidance of manufacturers proposing to treat American shale oils. The differences in the nature of the shale and in the industrial problems are discussed.

Brazil.—H. E. Williams, *Oil-Shales and Petroleum Prospects in Brazil* (Paper read before the American Institute of Mining and Metallurgical Engineers, September 1920).

Canada.—S. E. Slipper, *Sheep River Gas and Oil Field, Alberta* (Canada Geological Survey, 1921, Memoir 122). The report deals chiefly with the geology of the Sheep River area, but it treats also of well-boring data collected from various other districts in southern Alberta.

Dutch East Indies.—*Mineral Resources of the Dutch East Indies* (Engineering and Mining Journal, December 4, 1920, vol. 110, pp. 1085–1088). The chief petroleum-producing areas are the Langkat and Perlak districts in North Sumatra, Palembang in South Sumatra, Rembang and Sourabaya and the north-eastern part of Java, Koetei in Borneo and the Island of Tarakau. Refining is carried out at six establishments. Nearly all the Sumatra crude oils are especially rich in light products and, generally speaking, contain little or no paraffin. The Borneo crude oils vary considerably in composition, and the Java oils yield as a rule little benzine.

France.—E. Kohl, *The Working of Petroleum in Lower Alsace* (Glückauf, February 5, 1921, vol. 57, pp. 117–123). The development of the petroleum district near Pechelbronn is described. The yield has declined continuously from 110,000 tons a year in 1910 to 27,300 tons in 1919.

M. Devaux, *Petroleum Resources of France* (L'Age de Fer, July 10, 1920, vol. 36, pp. 430–432). A general review of the probabilities of the existence of oil-bearing strata in various districts in France.

Germany.—M. Henglein, *The Oil Shales of Germany* (Glückauf, January 22, 1921, vol. 57, pp. 73–78). A review is presented of all existing information concerning the geology and composition of the oil shales which occur in considerable abundance in many parts of Germany.

Mexico.—*Oilfields of Mexico* (Iron and Coal Trades Review, December 10, 1920, vol. 101, p. 794). The oilfields are situated in the lowlands behind the Gulf Coast, and extend from the southern part of the State of Tamaulipas in the north, through Vera Cruz and the eastern part of San Luis Potosi to the State of Tabasco in the south. The oil from the northern fields, such as Panuco, Topila, and Ebano, is generally dark or black, rather heavy, being full of asphalt. Farther south the oil is lighter and better, and in the southern Vera Cruz area oils are obtained containing large quantities of good illuminating oil. The analysis and specifications of Mexican fuel oil is approximately as follows: Carbon, 83.52 per cent.; hydrogen, 11.68 per cent.; sulphur, 3.27 per cent.; ash, 0.16 per cent.; undetermined, 1.37 per cent. Specific gravity at 60° F., about 0.950, with a flash point above 150° F.; viscosity at 100° F., 1500 seconds; calorific value, 18,900 B.T.U. per pound.

Russia.—A. Beeby Thompson, *The Oilfields of Russia* (Paper read before the American Institute of Mining and Metallurgical Engineers, August 1920). The author describes the characteristics of the chief oilfields and gives particulars of their production.

Trinidad.—G. A. Macready, *Petroleum Industry of Trinidad* (Paper read before the American Institute of Mining and Metallurgical Engineers, September 1920). The geology of the deposits is described.

United States.—J. R. Reeves, *Oil Shales of Indiana* (Engineering and Mining Journal, November 13, 1920, vol. 110, pp. 954–955).

E. F. Schramm, *Notes on the Oil Shales of South-Western Wyoming* (Bulletin of the American Association of Petroleum Geologists, 1920, vol. 4, No. 2). The author deals with the oil-producing shales of the Green River formation, which in one section totals 1784 feet in thickness.

E. T. Hancock, *The Mule Creek Oilfield, Wyoming* (United States Geological Survey, 1920, Bulletin 716-C).

E. T. Hancock, *The Lance Creek Oil and Gas Field, Niobrara County, Wyoming* (United States Geological Survey, 1920, Bulletin 716-E).

Venezuela.—A. H. Redfield, *Petroleum and Asphalt in Venezuela* (Engineering and Mining Journal, February 19, 26, 1921, vol. 111, pp. 354–357, 393–394). The geology and the development of the

oil-bearing districts are described, and a bibliography is given of the literature on the subject.

Treatment of Oil Shales.—L. Simpson, *The Commercial Retorting of Oil Shales* (Chemical and Metallurgical Engineering, October 20, 27, 1920, vol. 23, pp. 789–791, 813–816). The author discusses the utilisation of the vast deposits in the United States. It has been found that the Scotch type of retort, the result of development influenced by local conditions peculiar to Scotland, is not the most suitable or the most economical form of retort when used under conditions widely different from those existing in Scotland.

L. Simpson, *Plant Design for Hot Gas Pyrolytic Distillation of Shale* (Chemical and Metallurgical Engineering, February 23, 1921, vol. 24, pp. 341–345). The plant is designed to retort 2000 tons of shale each twenty-four hours, operating on the indirect heating process employing hot gases for conveying the reacting heat and resultant oil vapours from pyrolysis of the shale.

E. M. Bailey, *The Laboratory Distillation of Oil Shale for the Determination of the Available Yield of Crude Oil and Sulphate of Ammonia* (Petroleum Times, 1920, vol. 4, pp. 531–532).

K. Thomas, *Possible Uses for the Spent Shale from Oil Shale Operations* (Chemical and Metallurgical Engineering, March 2, 1921, vol. 24, pp. 389–390). This waste amounts to 60 to 80 per cent. of the material treated, and has a possible use as non-conducting material for electrical applications, and also in the manufacture of bricks.

M. J. Gavin, *Oil Shales and their Economic Importance* (Mining and Scientific Press, 1920, vol. 121, pp. 193–194).

Petroleum Refining.—A. E. Dunstan, *Petroleum Refining* (Petroleum Times, 1920, vol. 4, pp. 287–288). A description is given of the usual methods of refining and the different methods of cracking.

F. W. Padgett, *Production of Motor Gasoline from Heavy Oil Hydrocarbons* (Chemical and Metallurgical Engineering, September 15, 1920, vol. 23, pp. 521–525). The reactions taking place during cracking and the action of catalysts in the production of gasoline from petroleum are discussed.

Flow of Oil in Pipes.—A. C. Preston, *The Flow of Oil in Pipes* (Chemical and Metallurgical Engineering, September 29, October 6, 1920, vol. 23, pp. 607–613, 685–689). The author discusses a general method for determining the friction loss of any liquid flowing through pipes from its saybolt viscosity.

Uses of Oil.—A. J. Wilson, *Application of Liquid Fuel to Heavy Oil Engines* (Journal of the Institution of Petroleum Technologists, 1920, vol. 6, pp. 141–188). The injection systems for Diesel and semi-Diesel engines are discussed, and the specifications for various fuels are considered.

V.—NATURAL GAS.

Recovery of Petrol from Natural Gas.—G. A. Burrell, G. C. Oberfell, and C. L. Voress, *Gasoline by the Charcoal Absorption Process* (Chemical and Metallurgical Engineering, January 26, 1921, vol. 24, pp. 156–160). A description of the charcoal process for the extraction of gasoline from natural gas.

Extraction of Helium from Natural Gas.—C. G. Abbot, *Discovery of Helium and What Came of It* (Annual Report of Smithsonian Institution for 1918, Washington, 1920). An account is given of the discovery of helium, its properties and elements with which it is associated, and its separation from the natural gas yielded by certain gas wells in Texas and Oklahoma.

VI.—ARTIFICIAL GAS.

Gas-Producers.—*Wellman Mechanical Gas-Producer* (Foundry Trade Journal, March 17, 1921, vol. 23, pp. 247–248). An illustrated description is given of this producer, which will gasify 3000 lb. of ordinary bituminous coal per hour, forming a gas containing an average of 148 British thermal units per cubic foot, and with a loss in the ash of less than 1 per cent. of the combustible charged.

H. E. Bourcoud, *Gasification of Powdered Coal* (Chemical and Metallurgical Engineering, April 6, 1921, vol. 24, pp. 600–604). In previous attempts to gasify oil or pulverised fuel too little attention has been paid to the time necessary for the reaction and the temperature which must be maintained for its completion. In published descriptions the path of the gases through the producer is clearly too short to hold them the required time. The author submits a design for a producer with vertical combustion chamber, and in general outlines similar to blast-furnace hot-blast stoves.

Gas-Producer Practice.—N. R. Rees, *Gas-Producers* (Paper read before the Staffordshire Iron and Steel Institute, April 30, 1921: Iron and Coal Trades Review, May 6, 1921, vol. 102, pp. 636–637). It is pointed out that the essential features in the efficient and economical working of a producer are even distribution of coal, regulation of depth of fuel bed to obtain as complete a reduction as possible of CO_2 to CO , and also the decomposition of the steam, removal of ashes and clinker in as simple a manner as possible, and low cost of operating and installation, with quick and efficient gasification. Various attempts have been made to evolve a mechanical producer that gives an automatic method of feeding the fuel uniformly over the entire bed; also a method of agitating the fire-bed for the retention of a

level surface, and the automatic removal of the ash. Many producers, particularly of the hand-fed type, have been condemned on account of the high operating cost, which is due entirely to the improper provision of coal and ash handling equipment.

H. Hermanns, *Modern Development of Fuel Gasification* (Blast-Furnace and Steel Plant, November 1920, vol. 8, pp. 617-624). The development of modern gas-producers in Germany is described, with notes on the operation of producers and the processes by which the complete utilisation of all the constituents is obtained.

F. J. West and T. A. Tomlinson, *Modern Developments in the Manufacture and Utilisation of Coal Gas* (Paper read before the Manchester Geological and Mining Society: Iron and Coal Trades Review, December 3, 1920, vol. 101, p. 755).

K. Bunte, *Gas-Producers* (Journal für Gasbeleuchtung, August 21, 1920, pp. 541-545). The development of the coke-fired gas-producer is described, with an account of the gasifying of coke, briquettes, and raw brown coal. The advantages of central gas-producing installations are considered.

T. Limberg, *The Rational Utilisation of Bituminous Wet Brown Coal* (Braunkohle, August 21, 28, 1920, pp. 237-239, 249-254). The direct firing of brown coal results in a great waste of valuable constituents. The coal should be either treated in gas-producers with recovery of the by-products, or distilled at low temperature. These processes are described.

O. Essich, *Addition of Carbon Dioxide in the Gas-Producer* (Feuerungstechnik, 1920, vol. 8, pp. 184-185). In producers which are not blown with steam, the temperature of the gas passing off can be lowered by mixing carbon dioxide with the air-blast. One cubic metre of carbon dioxide to every 5 cubic metres of oxygen is sufficient to lower the temperature from 1000° to 500° C. The carbon dioxide can be added in the form of waste gases, the blast then having the composition: CO₂, 3.5; O₂, 17.5; and N, 79 per cent. An economy in coal is obtained equal to $\text{CO}_2 \times 100 / (\text{CO}_2 + \text{O}_2)$ per cent.

Producer-Gas from Peat (American Gas Engineers' Journal, 1920, vol. 113, p. 225). Tests have been carried out by the Norwegian Moor Co., Norway, on a peat containing 1.57 per cent. of ash and 21.7 to 43 per cent. of moisture. The tests indicate that it is possible to obtain in producer-gas about 75 per cent. of the calorific value of peat, which is much in excess of what can be obtained by direct combustion on a grate. In the gas-engine 20 to 35 per cent. of the heat value of the gas is utilised as against 10 to 15 per cent. in a steam-engine.

Gas-Producers with By-Product Recovery.—E. Roser, *Gas-Producers with Means for Recovery of Primary Tar* (Zeitschrift des Vereines Deutscher Ingenieure, October 16, 1920, vol. 64, pp. 857-864). From

1916 to 1918 trials were carried out by Messrs. Thyssen with a gas-producer of special type, with a by-product recovery plant attached. The results of the trials are set forth in full detail. Lubricating oil was one of the products extracted from the heavy tars. The cool gases, after removal of all the tarry substances, have not the same calorific value, but by preheating to 1250° C. they can be used with the same effect as fuel for the open-hearth. They require less air for combustion than ordinary producer-gas, and their heat value is more constant.

H. R. Trenkler, *Recovery of Primary Tar in Gas Production* (Zeitschrift des Vereines Deutscher Ingenieure, November 27, 1920, vol. 64, pp. 997-1002). The value of tar and tar products is so high that the recovery of tars by a low temperature distillation process has become an important factor in fuel economy. The rotary drum heated by gas-burners appears to be the most efficient type of apparatus for distilling coal at low temperature, as the process can be more easily controlled than in a stationary chamber; the efficiency is very high, and the construction permits the use of coal-dust. Precautions must be taken, however, to prevent the entrainment of dust in the gases, as it is liable to be precipitated with the tar, which greatly impairs its value.

Gas-producers are now being constructed which allow for the removal of the heavy tarry gases, the first product of distillation, through an upper chamber on the producer. The low temperature distillation takes place here, and the gases pass off at the top. The coal gradually descends into the larger main chamber, where complete gasification takes place, and the heating gases are taken off at the juncture of the narrow upper chamber with the wide lower one.

Recovery of Primary Tar in Gas-Producer Practice and its Treatment (Stahl und Eisen, March 10, 17, 1921, vol. 41, pp. 325-333, 364-370). On behalf of the Steelworks Committee of the German Society of Ironmasters three reports have been prepared and published by K. Linck describing the process of tar recovery with particulars of costs at the Burbacherhütte; by P. Jaworski on tar recovery as practised at the Bismarckhütte in Upper Silesia; and by F. Frank, dealing with the treatment of the tar and the products obtained by distillation.

F. Frank, *The Primary Tars. Their Recovery and Economic Importance* (Chemische Industrie, September 22, 1920, pp. 387-392). A general review of the various processes for recovery of primary tars and their economic consideration.

E. Jenkner, *The Determination of Tar, Dust, and Water in Producer-Gas* (Stahl und Eisen, February 10, vol. 41, pp. 181-185). An apparatus is described, the purpose of which is to effect the complete separation and estimation of the tar, gas, and water in samples of hot producer-gas.

Gwosdz, *Manufacture of Producer-Gas, with Special Reference to By-Product Recovery* (Braunkohle, July 10, 1920, pp. 165-167). The

influence of the physical constitution and of the ash content of the fuel on the gas is considered.

Producer-Gas Fired Boilers.—J. H. Bartlett, *A Producer-Gas Fired Boiler Installation* (Chemical and Metallurgical Engineering, November 24, 1920, vol. 23, pp. 1033–1035). At the collieries at Montrambert, Loire, coke breeze and mine waste are used for the production of gas for boiler firing on the surface combustion system. Trials show that 1 kilogramme of steam is evaporated by the combustion of about 1 cubic metre of gas, from water at 15° C., the average calorific value of the gas being 856 calories per cubic metre.

J. H. Bartlett, *Lean Gas as Boiler Fuel* (Iron Age, November 11, 1920, vol. 106, pp. 1261–1262). A short description is given of the trials recently made on firing a water-tube boiler with lean producer-gas at Montrambert, France.

Gas-Engines.—W. Bertram, *Further Development of the Two-Cycle Large Gas-Engine* (Stahl und Eisen, October 7, 1920, vol. 40, pp. 1335–1340). After tracing the progress in the development of the two-cycle valveless gas-engine, the author describes the constructional details of a new large gas-engine of this type built by the Dahlbruch Engineering Company, giving particulars of working results. By the new design various practical difficulties have been successfully solved.

W. Crooke, *The Advantages of Large Gas-Engines for Central Power Stations* (Electrician, November 5, 1920, vol. 85, pp. 547–548). The urgent need for fuel economy justifies more than ever the installation of large gas-engines, the idea that such engines are unreliable being based on early misconceptions which have prevented the proper development of the industry in this country. The advantages of co-operation when running gas power stations on waste gases are discussed, together with such considerations as design and tests. Details are given of the relative running on non-recovery producer-gas, coke-oven gas, and recovery producer-gas.

K. Kraft, *Large Gas-Engines and Blast-Furnace Gas* (Proceedings of the Cleveland Institution of Engineers, January 10, 1921, pp. 91–127). The author gives the result of tests made on a boiler utilising the exhaust gas from a 1640 brake-horse-power gas-engine at the Cockerill Works.

Gas-Fired Forge Furnace.—*The Application of Gas Fuel to Forging* (Iron Age, March 17, 1921, vol. 107, pp. 703, 745–746). The requirements of a satisfactory forge furnace fuel are discussed, and the advantages of gas compared with oil and coal are outlined.

Water-Gas.—A. E. Blake, *Water-Gas* (Proceedings of the Engineers' Society of Western Pennsylvania, December 1920, vol. 36, pp. 575–597). The manufacture, composition, and uses of water-gas are dealt

with Water-gas producers are illustrated. Owing to the high price of fuels and the uncertain supply of natural gas the use of water-gas is likely to increase.

[**Use of Blast-Furnace Gas.** *Economical Burning of Blast-Furnace Gas* (Iron and Coal Trades Review, February 18, 1921, vol. 102, p. 246). Illustrated particulars are given of the Weyman system of burning blast-furnace gas under boilers in operation at the works of the Cargo Fleet Iron Co., Ltd.

D. L. Ward and R. S. Reed, *Measurement of Blast-Furnace Gases* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921).

G. Schulz, *The Efficient Distribution of Blast-Furnace Gas as the Fundamental Principle in the Heat Economy of Iron and Steel Works* (Stahl und Eisen, February 3, 1921, vol. 41, pp. 145-149).

Utilisation of Waste Heat. T. R. Tate, *Application of Waste-Heat Boilers to Open-Hearth Furnaces* (Association of Iron and Steel Electrical Engineers, 1920, vol. 2, No. 12, pp. 1-10). The design of the proper size and type of boiler should be determined upon the basis of the weight of waste heat gases from any given size furnace. The weight can be calculated from the amount of carbon content in fuel and charge per ton of ingot steel produced, and from analyses of gases and their atomic weights.

G. R. McDermott and F. H. Willecox, *Open-Hearth Furnace Waste-Heat Utilisation* (Paper read before the Western Society of Engineers, November 15, 1920, vol. 107, pp. 899-900).

VII.—COAL WASHING AND HANDLING.

Coal Storage. O. P. Hood, *Coal Storage* (Paper read before the Pennsylvania Electric Association; Iron and Coal Trades Review, January 14, 1921, vol. 102, p. 53). The author discusses some causes of spontaneous combustion of coal.

H. H. Stock, *Safe Storage of Coal* (United States Bureau of Mines, 1920, Technical Paper 235).

Coal Washing. E. Bury, W. Broadbridge, and A. Hutchinson, *Feath Flotation as Applied to the Washing of Industrial Coal* (Transactions of the Institution of Mining Engineers, February 1921, vol. 60, pp. 243-253). The authors describe the practice at Skinninggrove, and give the results of experiments.

Feath Flotation Applied to the Separation of Coal (Iron and Coal Trades Review, February 11, 1921, vol. 102, p. 197). The process is directly applicable to: (1) The removal of dirt and incombustible

matter from crushed coal destined for coking purposes ; (2) the preparation of clean coal for briquetting ; (3) the recovery of coal from screen pickings ; (4) the recovery of coal from washery slurry ; and (5) the recovery of coal lying in silt pond or in old pit heaps.

Dry Cleaning of Coal.—E. O'Toole, *Dry Cleaning of Coal by Means of Tables* (Paper read before American Iron and Steel Institute, May 27, 1921). A dry concentrating and jigging machine has been successfully applied to the cleaning of coal. Instead of water, air is used as the floating medium ; the coal is properly sized before feeding on to the table, and the separation is secured by taking advantage of the difference in the weight of materials. Air supplied by a blower passes upwards through a number of small perforations in the jigging table.

Coal Handling.—*Aerial Ropeway at Frickley Colliery* (Iron and Coal Trades Review, October 29, 1920, vol. 101, pp. 577-578). The total length of ropeway is about 1920 feet, divided into seven spans. It is designed to carry 25 tons per hour, in unit loads of 10 cwts. each.

Coal Briquetting.—E. Stansfield, *Principles and Practice of Fuel Briquetting* (Paper read before the Canadian Institute of Mining and Metallurgy : Colliery Guardian, October 29, 1920, vol. 120, p. 1244). American and Canadian practice is described.

“ *Victory* ” *Ovoid Briquette Press* (Iron and Coal Trades Review, December 10, 1920, vol. 101, p. 798). Illustrated particulars are given of the above type of press.

PRODUCTION OF IRON.

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I.—MANUFACTURE OF PIG IRON.

Blast-Furnace Plant and Equipment.—*Blaenavon Iron and Steel Works* (Iron and Coal Trades Review, October 22, 1920, vol. 101, pp. 541-544). The pig iron output is entirely hæmatite, smelted from Spanish ore. There are three blast-furnaces with a total annual output of 150,000 tons. The gas-cleaning plant is of the Halberg-Beth type, consisting of three standard filter boxes, each having a rated capacity of 1,000,000 cubic feet per hour.

H. Cole Estep, *British Iron and Steel Centres* (Iron Trade Review, April 28, 1921, vol. 68, pp. 1167-1169). The first of a series of articles describing the geographical and physical features of the iron and steel producing areas of the United Kingdom.

New Blast-Furnaces of the Replogle Steel Co. (Iron Age, October 7, 1920, vol. 106, pp. 895-901). Two new furnaces have been built at Wharton, New Jersey, forty miles from New York, for the Replogle Steel Co. They supersede older furnaces belonging to the Wharton Steel Co. The plant has cost three million dollars. The furnaces are 90 feet high, 21 feet 6 inches at boshes, and 17 feet 6 inches at crucible. The bosh angle is $79^{\circ} 13'$, and the furnaces, which are rated at 500 tons per day, each have McKee revolving tops. Each furnace is provided with four 22 by 100 feet Roberts stoves with short flame burners.

New Blast-Furnace Recently Completed (Iron Age, March 3, 1921, vol. 107, pp. 570-575). The new 600-ton blast-furnace recently completed at the plant of the Pittsburgh Crucible Steel Co. is described and illustrated. The stack is 92 feet high with a hearth 18 feet diameter, bosh 22 feet 6 inches, and a stock line 16 feet diameter. Three stoves are used, and the gas is cleaned by the Kling-Weidlein dry system.

W. Mathesius, *Large Blast-Furnace Hearths* (Paper read before the American Iron and Steel Institute, October 1920). One of the

advantages of the larger hearth is its greater accessibility. With increased diameter, greater peripheral distances result in arranging feed and discharge pipes for cooling water, more space is available around the tuyeres and the columns, as well as between the iron and cinder runners near the furnace, so that, on the whole, the cast-house work and also the mechanical maintenance become easier and simpler. The average hearth diameter of all 22 feet bosh furnaces at the South Chicago plant of the Illinois Steel Company was increased from 16 feet 6 inches in 1911 to 18 feet 6 inches in 1919, and the best average monthly production of these furnaces equalled 512 tons per furnace per day in December 1911 as against 556 tons in May 1920. A section of No. 6 blast-furnace at the South Works of the Illinois Steel Company, which has been in successful operation for two years, shows a hearth diameter of 20 feet 9 inches, and a bosh diameter of 23 feet 6 inches.

American Blast-Furnaces Remodelled (Iron Age, November 18, 1920, vol. 106, pp. 1318-1319). A description is given of the improvements recently made in the two Columbus blast-furnaces and the entire remodelling of the hot-blast stoves of the American Rolling-Mill Company. While new concrete foundations were being put in, the furnaces were held up by means of bridge girders.

Rebuilt Furnace Conserves Labour (Iron Trade Review, October 21, 1920, vol. 67, pp. 1123-1126). The remodelled blast-furnace of the Belfont Iron Works, Ironton, Ohio, is illustrated and described. The blast-furnace had a capacity of 150 tons daily, and has been made capable of producing 250 tons daily.

Stack for Foundry Iron (Iron Trade Review, October 14, 1920, vol. 67, pp. 1068-1070). An illustrated description is given of the reconstructed blast-furnace of the Low Moor Iron Co., West Virginia. The new stack is built on the original columns and mantle and is 76 feet high with 12½ feet hearth diameter.

Blast-Furnace Plant Embodies New Features (Iron Age, January 6, 1921, vol. 107, pp. 35-41, 105). The new 500-ton blast-furnace and equipment at the plant of the St. Louis Coke and Chemical Co., Granite City, Illinois, is illustrated and described.

Turbo-blowing Plant at Ormesby Ironworks (Iron and Coal Trades Review, March 4, 1921, vol. 102, pp. 313-314). The turbines are the impulse high-pressure type operating with a steam pressure of 160 lbs. per square inch with 100° F. of superheat. The speed ranges between 2750 and 3000 r.p.m. The turbo-blowers are duplicate units, Rateau type, multi-stage, single flow machines capable of a normal output of 20,000 cubic feet of free air per minute.

A Modern American Blast-Furnace Stocking and Charging Equipment (Iron and Coal Trades Review, January 7, 1921, vol. 102, p. 15; Iron Age, December 9, 1920, vol. 106, pp. 1541-1542). An illustrated description of the charging equipment at the Sheridan plant of the Lavino Furnace Co., Pennsylvania.

Electricity at Blast-Furnaces.—(Electrician, November 26, 1920, vol. 85, pp. 620–622.) An illustrated description is given of electrical equipment for blast-furnaces, including large electrically operated blast-furnace chargers. The chargers described are those installed at the Port Talbot Works of Messrs. Baldwins, Ltd.

L. A. Touzalin, *Reducing Blast-Furnace Hazards* (Paper read before the United States National Safety Council: Iron Trade Review, October 7, 1920, vol. 67, pp. 987–989). The author discusses safety appliances and the best methods for protecting the workmen engaged at blast-furnaces.

Blast-Furnace Practice.—H. Thaler, *The Production of Manganiferous Pig Iron using Low-Grade Manganiferous Substances, in Particular the Siegerland Blast-Furnace Slags* (Stahl und Eisen, February 24, March 10, 1921, vol. 41, pp. 249–253, 338–343). When the supplies of manganese in Germany began to run short during the war, attention was directed to the vast quantities of slag in the dumps of the Siegerland blast-furnace works, in which the manganese averaged 12·25 per cent. The article describes how these slags were utilised as a substitute for the manganiferous ores of the Siegerland in the production of spiegel. The cost of production was increased by about 15 per cent., and the furnace yield was reduced by about 20 per cent.

E. Pierre, *Reducing Reactions in the Blast-Furnace* (Revue Universelle des Mines, December 1920, vol. 7, Series 6, pp. 301–321). The author deals with practice in the smelting of minette ore, and his studies extend to the action of the gases on the coke and on the ores.

A. Wagner, *Effect of Temperature, Pressure, and Moisture of the Atmospheric Air on the Working of the Blast-Furnace* (Stahl und Eisen, October 21, 1920, vol. 40, pp. 1397–1403). The theoretical effect of temperature, pressure, and moisture on the weight of the atmosphere is determined according to the laws of the mechanical theory of heat. The curve for the volumetric weight of the atmospheric air shows agreement with the twelve months' records of the atmospheric pressure at the meteorological station at Essen-Hügel. A graphic representation of the working results of a blast-furnace in the neighbourhood indicates that with the blowing-engine driven at the same speed, the lowest blast-pressure and highest furnace output occur in the month of May. The coke consumption is not affected by the changing moisture of the atmosphere, but varies approximately conversely with the yield of the ore. The information yielded by the observations will serve as a new starting-point for experiments with enriched blast.

Y. A. Dyer, *Foundry Pig Iron in Birmingham District* (Iron Age, April 7, 1921, vol. 107, pp. 907–909). The author deals briefly with the developments in pig iron manufacture in the Birmingham district of Alabama, and discusses the advantages of machine-cast pig over

sand-cast pig. The machine-cast pig has a lower melting point owing to higher combined carbon, thereby effecting a saving in fuel and flux, and minimising slag volumes.

Y. A. Dyer, *Some Defects in Foundry Pig Irons* (Iron Age, April 28, 1921, vol. 107, pp. 1093-1094).

J. P. Dovel, *Reasons Why Foundry Iron should be Sand-Cast* (Iron Age, April 21, 1921, vol. 107, p. 1035). The author discusses briefly the limitations in the use of machine-cast pig for foundry purposes.

E. Piwowarsky, *Gases in Pig Iron* (Stahl und Eisen, October 14, 1920, vol. 40, pp. 1365-1366). Tests were made to determine the nature of the gases given off from liquid pig iron. The metal for the experiments was taken from a blast-furnace of 480 cubic metres capacity working on basic pig, the blast being at a pressure of about 5 lbs. and at a temperature of 670° to 680° C. Three samples of liquid pig iron were taken, one at the beginning, one in the middle, and one at the end of tapping. These samples were run into upright tapering moulds, through which a stream of nitrogen had been passed till the atmospheric air was expelled. The tops of the moulds were closed with an iron cover through which a tube passed, leading to a glass receiver filled with water. The moulds were filled by bottom pouring, the nitrogen escaping by another opening in the cover till they were quite full. The latter outlet was then closed, the connection with the receiver opened, and the gases from the metal expelled the water from the receiver till this was filled. The following was found to be the composition of the gas:

	CO ₂ .	CO.	H ₂ .	N ₂ .
At beginning of tapping	0.60	30.80	49.60	18.60
	0.84	24.0	30.80	44.26
In the middle of tapping	0.74	36.40	42.83	19.80
	0.55	39.62	48.02	11.54
At end of tapping	0.40	43.30	45.80	10.50
	0.30	42.20	48.30	9.10

After solidification of the metal the amount of gas given off was very small.

Prevention of Salamanders (Iron Trade Review, March 31, 1921, vol. 68, pp. 896-897). A method is described which is employed at the blast-furnaces of the American Steel and Wire Co., Cleveland, for the prevention of salamanders or bears. During a blow out it is the practice to cast as much iron as possible through the taphole and to drain the metal remaining in the furnace through a passage sloping downward from the bottom of the hearth to the furnace subjacket.

F. Prudhomme, *Green Wood in the Blast-Furnace* (Iron Age, January 13, 1921, vol. 107, pp. 121-122). The blast-furnaces at the Corral steel plant, Chile, are operated on the Prudhomme system for burning green wood instead of charcoal. The wood is charged hot and dry into the blast-furnace. In the upper part it is charred, arriving in the condition of finished charcoal at about 33 feet above the plane

of the tuyeres. The charring is made easier by a set of small tuyeres, which supply hot-blast to within a few yards of the top of the furnace, keeping the top always dry. The thermal balance of the furnace is given.

G. Neumann, *The Heat Currents in the Checkers of Stoves and Regenerators* (Stahl und Eisen, November 4, 1920, pp. 1473-1479). The influence of the thickness of the bricks, used for the checkers, in increasing or diminishing their capacity for storing and giving up heat is discussed. Apart from a reduction in the heating surface it makes little difference if bricks up to $3\frac{1}{2}$ inches thick are used.

C. E. Roberts, *Some Blast-Furnace Problems of To-day* (Paper read before the Staffordshire Iron and Steel Institute, December 11, 1920: Iron and Coal Trades Review, December 17, 1920, vol. 101, p. 840). The author discusses the changes due to abnormal war-time conditions, with special reference to practice in the South Staffordshire district.

Cleaning of Blast-Furnace Gas.—*New Blast-Furnaces of the Replogle Steel Company* (Iron Age, October 7, 1920, pp. 895-901). The Bachman gas-cleaning plant erected at the works of the Replogle Steel Co., New Jersey, is described and illustrated.

E. Hubendick, *The Cleaning of Blast-Furnace Gas* (Jernkontorets Annaler, 1920, No. 4, vol. 75, pp. 79-95). The composition and heat values of the gases from blast-furnaces are compared with those from electric smelting furnaces, the conditions being those obtaining in Swedish practice. The advantages of gas-cleaning are discussed.

L. B. Breedlove, *Blast-Furnace Gas-Cleaning Equipment* (Iron Age, January 6, 1921, vol. 107, pp. 11-14). An illustrated description is given of the Kling-Weidlein dry gas cleaners in operation at the blast-furnace plant of the Ford Motor Co., Rouge River.

G. B. Cramp, *Direct Recovery Process for Flue Dust* (Blast-Furnace and Steel Plant, March 1921, pp. 198-202; Iron Trade Review, March 24, 1921, vol. 68, pp. 836-839; Iron Age, March 24, 1921, vol. 107, pp. 775-778). A wet-washing system is described, in which the heavier dust is recovered direct, and is immediately available for charging into the furnace without briquetting or sintering.

E. Bury, A. Bury, O. Ollander, and F. Bainbridge, *Electrostatic Deposition of Dust from Blast-Furnace Gas and the Extraction of Potash Therefrom* (Paper read before the Cleveland Institution of Engineers: Iron and Coal Trades Review, February 11, 1921, vol. 102, pp. 191-192). The Lodge process at Skinningrove is described.

A. Gouvy, *Recent Developments in the Cleaning of Blast-Furnace Gas* (Revue de Métallurgie, Mémoires, October 1920, vol. 17, pp. 677-686). The use of high-tension current, by the Cottrell method, for the precipitation of dust from blast-furnace gas is briefly described.

H. J. Bush, *Electrostatic Separation* (Electrician, November 5, 1920, vol. 85, pp. 533-535). A description of the Cottrell process, with

reference to the plant of the Workington Iron and Steel Co. The cause of early failures and the means of securing success in practice are discussed.

Cottrell Processes of Electrical Precipitation (Mining and Scientific Press, April 9, 1921, vol. 122, pp. 495-500). The early investigations of Cottrell are dealt with, and the theory and principles of the process is discussed. An extensive bibliography of the subject is appended.

Electric Smelting of Iron.—Baron Gerard de Geer, *Electric Smelting of Pig Iron at Domnarfvet, Sweden* (Chemical and Metallurgical Engineering, March 9, 1921, vol. 24, pp. 429-433). The early operations at the Domnarfvet Ironworks and the conditions leading to the adoption of electric furnaces are outlined. The possibilities of using other reducing agents than charcoal, and pit furnaces instead of shaft furnaces, are also discussed.

Synthetic Cast Iron.—H. L. Hatt (Iron Trade Review, January 13, 1921, vol. 68, pp. 149-159). The manufacture of pig iron from steel scrap in a 5-ton electric furnace is described. The charge was made up as follows: 10,000 lbs. of steel shell turnings; 600 lbs. of charcoal; 250 lbs. of 50 per cent. ferro-silicon, and 300 lbs. of lime. The composition of the iron was: Carbon, 3.15 to 3.50 per cent.; silicon, 1.25 to 1.50 per cent.; manganese, 0.60 to 0.70 per cent.; phosphorus, 0.03 to 0.04 per cent.; and sulphur, 0.012 to 0.020 per cent. It usually took from three to four hours to melt, depending on the voltage. The iron produced was cast into pigs.

W. L. Morrison, *Manufacture of Synthetic Cast Iron in the Electric Furnace* (Electric World, 1920, vol. 75, pp. 1490).

Manufacture of Ferro-Alloys.—R. M. Keeney and J. Lonergan, *Manufacture of Ferro-Manganese in the Electric Furnace* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921).

The Manufacture of Ferro-Manganese in the Electric Furnace (Foundry Trade Journal, January 20, 1921, vol. 23, p. 65). The type of furnace which is now meeting with most favour is of the stationary open-top type, three-phase, three-electrode type, and the furnaces range in size from 300 kilowatts to 4000 kilowatts, lined with carbon and magnesite. The recovery of the total manganese, as contained in the cleaned metal, does not usually exceed 70 per cent. of the total manganese charged into the furnace.

J. Escard, *Electrometallurgical Production of Ferro-Titanium* (L'Industrie Chimique, 1920, vol. 7, pp. 188-190). The author reviews the Rossi and Borchers processes, and refers to the experiments of Guillet, Braune, and Lamort.

J. G. Dailey, *Acid Electric Furnace Ferro-Tungsten* (Paper read

before the American Institute of Chemical Engineers, December 5, 1919). The author describes the manufacture of 75 per cent. ferro-tungsten in a small two-phase electric furnace.

E. Liévenie, *Ferro-Alloys* (L'Age de Fer, November 25, 1920, vol. 36, pp. 733-735). A short account of the manufacture and uses of the principal ferro-alloys, including ferro-manganese, ferro-silicon, ferro-chrome, ferro-tungsten, ferro-molybdenum, ferro-vanadium, ferro-boron, and ferro-uranium.

C. G. Fink, *Alloys of the Past and Present* (Chemical and Metallurgical Engineering, September 8, 1920, vol. 23, pp. 471-473). A brief account of recent developments in the production of pure metals and ferro-alloys.

Iron Industries of Various Countries.—C. Lemaire, *The Mining and Metallurgical Industry of Luxemburg* (L'Age de Fer, October 10, 1920, vol. 36, pp. 626-628). The output of iron ore in Luxemburg in 1919 was 3,112,472 tons as compared with 3,131,400 tons in 1918, while the average price rose from 4.51 francs to 8.15 francs. The output per workman employed in 1913 averaged 1200 tons a year, and in 1919 it averaged 855 tons. The production of pig iron and steel for the three years 1917-18-19 was as follows :

	Pig Iron.	Steel Ingots.	Steel Castings, Electric .
1917 . . .	1,528,865	1,053,596	33,126
1918 . . .	1,266,671	857,937	29,712
1919 . . .	617,422	366,231	4,564

The great dearth of coal and the abrupt political changes following the Armistice were responsible for the great falling off in production in 1919.

A. H. Brooks and M. F. La Croix, *The Iron and Associated Industries of Lorraine, the Saar District, Luxemburg, and Belgium* (United States Geological Survey, 1920, Bulletin 703). The resources of iron ore and coking coal of these districts are dealt with, and the conditions governing the manufacture of iron and steel are discussed. Tables are also given showing the pre-war productions of raw materials and iron and steel.

B. Schapira, *Czechia Holds Key to Iron and Steel Situation in Central Europe* (Iron Trade Review, April 7, 1921, vol. 68, pp. 962-969, 976). Particulars are given of the iron and steel industry of Czecho-Slovakia, and an illustrated description is given of the following plants : Witkowitz Bergbau-Eisenhütten Gewerkschaft, Prager Eisen-Industrie Gesellschaft, and the Berg- und Hüttenwerks Gesellschaft.

N. G. Caranfil, *The Iron Industry of Great Roumania* (Génie Civil, December 25, 1920, vol. 77, pp. 533-535). By the acquisition of the Banat and Transylvania Roumania obtained an iron industry of some importance. The works taken over comprise three establishments of the Reschitza Company, two belonging to the Rimamurany

Company, and one State-owned works, with nine blast-furnaces altogether. The mines at present can furnish about 13 million tons of coal and 500,000 tons of high-grade iron ore a year. The yearly capacity of the iron and steel works is about 250,000 tons of pig iron and 160,000 tons of steel. A map is given showing the localities of the ironworks and mines.

A. W. Richards, *The Coal, Iron, and Steel Industries of South Russia* (Electrician, November 5, 1920, vol. 85, pp. 539-540). A note of the mineral resources of South Russia, and their future prospects, with special reference to such electric developments as have taken place, and the economic considerations to which regard must be given in any scheme for resettling and re-establishing iron and steel works on a pre-war basis.

Proposed Vancouver Island Steel Plant (Iron and Steel of Canada, August 1920, vol. 3, p. 204). A short note as to the prospects of establishing blast-furnaces and steel plant on Vancouver Island.

G. H. Blenkinsop, *The South African Iron and Steel Industry* (South African Mining and Engineering Journal: Iron and Coal Trades Review, April 1, 1921, vol. 102, pp. 468-469). The Union undoubtedly contains large occurrences of iron ores, but only a portion of the ore is suitable for the manufacture of acid steel. Some of the ore contains so much titanium that at present it has no commercial value. Up to the present time the quantity of coal discovered suitable for coke-making for blast-furnace practice is very limited; in fact, the quantity is so limited that the erection of blast-furnaces for the manufacture of iron is not justified.

C. P. Perin, *The Recent Development in the Iron and Steel Industry of India* (Paper read before the American Iron and Steel Institute, October 22, 1920). After giving a brief account of the history of iron-making in India, the author describes the new installation of the Tata Iron and Steel Company.

State Iron and Steel Works in Queensland (Iron and Steel of Canada, August 1920, vol. 3, p. 207). In connection with the scheme of the Queensland Government to establish a State iron and steel works at Bowen, on the east coast of Australia, an option has been secured on the iron ore deposits on islands near Yampi Sound on the north-west coast, which are said to be among the richest and most accessible in the world, the grade of the ore being 69 per cent. It is intended to blend these with the Queensland ores containing 67 per cent. of iron.

Iron Industry in the Argentine (Engineer, November 12, 1920, vol. 130, p. 474). On the Atlantic coast of Argentina, especially at Necochea in the north, ferriferous sands exist in large quantities. Methods for separating the different substances contained in the sand have been tried with success, giving the following result: Magnetite, 60 per cent.; ilmenite, 38 per cent.; common sand, 2 per cent. The magnetite contains about 59 per cent. of iron and the ilmenite about 50 per cent. For smelting it is suggested that electric energy might

be developed by using crude petroleum from local wells. An abundant supply of charcoal could also be obtained in the country.

Japanese Blast-Furnaces (Iron Age, October 21, 1920, vol. 106, pp. 1045-1047). A brief description of the principal blast-furnace plants in Japan is given. A similar review, with details as to the iron and steel resources, iron ore deposits, and coalfields is given by L. P. Sidney, *Vulcan in Nippon*, *Times Trade Supplement*, April 16, 1921, pp. 16-17.

History of Iron.—J. D. Knox, *A Century of Iron-Making in Southern Ohio* (Iron Trade Review, September 30, 1920, vol. 67, pp. 919-926). An illustrated description of the practice and plants for the manufacture of pig iron in Southern Ohio from the beginning of the last century.

Systematic Destruction by the Germans of the Ironworks in Northern and Eastern France (Génie Civil, November 13, 1920, vol. 77, pp. 385-391). A further account of the complete destruction of French iron and steel works before the German armies were driven out of north-east France, with photographs showing the sites of machinery and plant destroyed or removed.

II.—BLAST-FURNACE SLAGS.

Uses of Slag.—P. Decamps, *Constitution and Use of Blast-Furnace Slags* (Revue Universelle des Mines, January 1, 1921, vol. 8, pp. 1-18, 73-89). A general description of the nature of the slags which can best be used for the manufacture of slag cement and bricks, the methods of manufacture, and the various purposes to which slag and slag cement can be applied.

Use of Old Slag for Road-Making (Iron and Coal Trades Review, October 22, 1920, vol. 101, p. 544). A short description is given of the Ransome combined drying and mixing plant for the conversion of slag into tar macadam.

Sampling Blast-Furnace Slag.—W. M. Chegwiddden, *Sampling Blast-Furnace Slags* (Iron Trade Review, December 23, 1920, vol. 67, pp. 1750-1751). The author discusses the methods of sampling, and gives a table which indicates that the sulphur in the slag bears a definite relation to that in the corresponding pig iron.

Tests of Slag.—H. Burchartz, *Tests on Blast-Furnace Slag* (Stahl und Eisen, February 10, 1921, vol. 41, pp. 193-200). The results of the tests show that cement from blast-furnace slag is quite sufficiently impervious to water and air to serve as a covering for reinforcing steel bars and steel structural material. In its capacity for hardening in

sea-water and its durability in sea-water it is fully equal to ordinary cement.

M. Gary, *Comparative Tests of Air-set and Water-set Iron-Portland Cement* (Mitteilungen aus dem Kgl. Materialprüfungsamt, 1915, vol. 33, Nos. 5 and 6, pp. 271-290). The results of the tests show in general that iron-Portland cements (slag cements), as at present compounded, set considerably harder after fourteen days under water than they do in air.

H. Burchartz, *Properties of Portland Cement, Iron-Portland Cement, Blast-Furnace Cement, and other Hydraulic Binding Materials* (*Ibid.*, 1919, vol. 37, pp. 85-109).

III.—DIRECT PROCESSES.

F. Wüst, *Direct Production of Iron* (Zeitschrift des Vereines deutscher Ingenieure, November 27, 1920, vol. 64, p. 1011). The article is a criticism of the Basset process. The problem of the direct production of iron is said to have been solved by Basset, who claims to be able to produce malleable iron 70 per cent. cheaper than by the ordinary method of making wrought iron, the cost of the necessary plant being 80 per cent. less. He attempts to avoid the reoxidation of the reduced iron from carbon dioxide by firing with powdered coal in air at 1000° burnt to carbon monoxide only. This proved impracticable, and moreover the temperature necessary to melt wrought iron is not attained. It has then been tried to burn half the carbon to carbon dioxide and the remainder to carbon monoxide, but the oxidising effect on the reduced iron results in a large proportion of iron passing into the slag. By means of a thermal and chemical balance-sheet Wüst shows that Basset's calculations concerning the fuel consumption are erroneous, and the cheapening of the cost of production and of the plant is not attainable by means of his process. For any direct method of reducing iron, gaseous fuel would appear to be unsuitable; solid carbon alone would have a sufficiently reducing effect. The only prospect for a successful direct process would be, to utilise the metal bath of an open-hearth furnace for the purpose of dissolving the reducing carbon and to charge the ore direct into the bath, as is done in the pig iron ore process. The necessary speed of reduction would then be obtained.

R. E. Hore, *Utilisation of Ontario Iron Ores: A New Metallising Furnace* (Canadian Mining Journal, October 1, 1920, vol. 41, pp. 796-797). With a view to utilising the low grade or fine ores which occur in some abundance in Ontario, a process has been devised for reducing the ore in a fine state mixed with coke, in an air-tight retort heated externally by gas or fuel oil and then by the waste gases from the retort. The metallised product or sponge falls through a trap into

an air-tight conveyor, which delivers it hot to the electric furnace. An illustration of the plant is given.

J. W. Moffat, *A Direct Process for making Iron and Steel from Ore* (Iron and Steel of Canada, October 1920, vol. 3, pp. 271-274). A full description of the same furnace, known as Moffat's metallising furnace, is published.

Steel from Iron Oxide Sand in Japan (Engineer, December 24, 1920, vol. 130, p. 243). Investigators working for the Japanese War Department report the discovery of a method for the extraction of iron from the volcanic iron sands of Japan, hitherto regarded as wholly refractory. The experiments on a commercial scale at the Penchihiu works have yielded very satisfactory results.

FOUNDRY PRACTICE.

Cupola Practice.—W. Rawlinson, *Modern Cupola Practice* (Paper read before the Institution of British Foundrymen : Foundry Trade Journal, April 14, 1921, vol. 23, pp. 337–339).

K. Berthold, *Experiments with Supplementary Oil-Firing in Cupola Melting* (Stahl und Eisen, March 24, 1921, vol. 41, pp. 393–399). On account of the great scarcity of coke in Austria experiments were made in a large foundry with a view to ascertaining whether oil could be successfully used in cupola melting. Three oil-burners were built into the cupola and the number of tuyeres was reduced to three. At starting somewhat less than the usual quantity of coke was charged (510 kilogrammes instead of 540 kilogrammes), and thereafter the quantity of coke added was 4 to 5 kilogrammes per 100 kilogrammes of metal tapped, the oil consumption being 1 kilogramme per 100 kilogrammes of metal tapped. The hourly rate of melting was increased by 30 to 50 per cent., and the temperature of the cast was fully maintained.

H. L. Campbell, *Method for Determining Cupola Charges* (Foundry Trade Journal, November 1920, vol. 22, pp. 856–857). A chart has been prepared by the author by means of which the correct quantities of the different pigs and scrap making up the charge may be ascertained direct.

Handling Molten Iron at the Cupola (Canadian Foundryman : Foundry Trade Journal, October 1920, vol. 22, p. 788). Several ingenious devices are described for the tapping of cupolas, as practised at a Canadian foundry. Instead of ramming in the breast to form the taphole, a firebrick with two holes in it is used. It is so placed that the bottom hole is in line with the trough. The second hole is an inch or more above this. Both holes are plugged when the blast is turned on, and when sufficient metal is melted the bottom hole is tapped. As the melting proceeds and the metal is accumulating in the furnace, the top hole is tapped and the reserved metal brought down. A tilting or double spout is also used, which consists of an iron trough from 2 or 3 feet in length attached to the ordinary cupola spout. It is open at both ends, and is attached to the cupola spout in such a manner as to have the top of it slightly below the bottom of the cupola spout, and so situated that the iron as it flows from the spout strikes it in the centre. A lever is attached to it for tilting.

Modern Two-Cupola Foundry at North Tonowanda (Iron Age, October 21, 1920, vol. 106, pp. 1042-1043). A double purpose is served by the cupola blower installed at a foundry at North Tonowanda, New York, where, on dumping the cupola, the blower is made, by shifting the gates, to draw away the smoke and gases at the cupola and discharge them into the atmosphere.

W. Bowen, *The Application of Pyrometers to Foundry Work* (Chemical Age, 1920, vol. 3, pp. 556-557).

C. H. Desch, *Blowholes in Castings* (Paper read before the Institution of British Foundrymen, November 5, 1920: Foundry Trade Journal, January 13, 1921, vol. 23, pp. 36-37).

R. Moldenke, *Zirconium as Deoxidiser in Cast Iron* (Foundry, 1920, vol. 48, pp. 878-879). The author used for his experiments an alloy containing 30.6 per cent. of zirconium. Small percentages behaved well in melting and indicated a purifying action. The larger percentages chilled the metal considerably so that it was difficult to pour successfully. A table is given showing the composition of the cast iron, the amount of zirconium added, the breaking strength and the deflection.

F. H. Hurren, *Wasters* (Presidential Address before the Institution of British Foundrymen, October 6, 1920: Foundry Trade Journal, December 1920, vol. 22, pp. 931-934). The many causes of wasters or scrap castings are discussed, and suggestions are given for their elimination.

G. L. Lacher, *New Charging Machine in Rundle Foundry* (Iron Age, January 6, 1921, vol. 107, pp. 4-8). An illustrated description is given of a cupola charging machine in operation in the foundry of the Rundle Manufacturing Co., Milwaukee. A monorail crane carries the bucket into the cupola, where it is lowered to a point just above the level of the charge. The bucket is an adaptation of the blast-furnace bell hopper.

Composition of Foundry Iron.—R. Moldenke, *Grey Iron Castings* (Mechanical Engineering, August 1920, vol. 42, pp. 437-439). A comprehensive table of analyses recommended for various classes of castings is given, and the various factors affecting the composition and the properties are considered.

Steel Foundry Practice.—R. Moldenke, *The Electric Furnace in the Iron Foundry* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921). The advantages of the basic hearth electric furnaces for foundry use are discussed, and particulars are given of the operating cost.

G. K. Elliott, *Electric Furnaces and the Sulphur Problem in Cast Iron* (Paper read before the Annual Convention of the American Foundrymen's Association, Columbus, Ohio, October 5: Iron Age, October 7, 1920, vol. 106, pp. 919-920). The behaviour of sulphur

in cast iron and in steel made in an electric furnace is discussed, together with the question of segregation. The great advantage of securing low sulphur by electric melting and refining is specially dealt with.

E. F. Cone, *Electric Furnaces as Melting Mediums* (Paper read before the American Foundrymen's Association : Iron Age, October 21, 1920, vol. 106, pp. 1059-1061). The author reviews electric furnace plant and practice in the United States and in Canada and gives statistics of the installations. The growing adoption of such furnaces in foundry work is shown by no less than 137 out of a total of 385 in operation on September 1, 1920, being so employed. The furnaces most used for such purposes appear to be the Ajax-Wyatt, the Baily, the Detroit, and the Booth.

J. W. Galvin and C. N. Ring, *Heat Modifies Acid Furnace Reaction* (Foundry, 1921, vol. 49, pp. 72-74). The author deals with foundry practice using the acid electric steel furnace.

D. D. MacGuffie, *The Manufacture of Steel Castings* (Paper read before the Institution of British Foundrymen : Foundry Trade Journal, March 3, 1921, vol. 23, pp. 197-200). The author discusses general steel foundry practice, using the Stock oil-fired converter, the Tropenas converter, and the electric furnace.

R. B. Farquhar, jun., *Pouring, Gating, and Feeding Steel Castings* (Paper read before the American Foundrymen's Association, October 1920). The problems encountered in the pouring of steel castings are discussed in detail.

The Works of Steel Castings Ltd. (Foundry Trade Journal, March 24, 1921, vol. 23, pp. 262-264). The layout of this foundry, which is situated in Glasgow, is described. The melting plant consists of a 6½ ton and a 15-20 ton furnace. Gas is supplied from three producers.

H. E. Diller, *Electrically Operated Foundry* (Iron Trade Review, February 24, 1921, vol. 68, pp. 559-563). The equipment and layout of the foundry of the Emery Steel Castings Co., Baltimore, for the production of small steel castings is described. A 1-ton electric melting furnace is in operation, and electricity is used for the annealing furnaces and core-ovens.

Semi-Steel.—E. Wheeler, *Cast Iron versus Semi-Steel* (Paper read before the Manchester Association of Engineers : Foundry Trade Journal, February 3, 1921, vol. 23, pp. 99-100). The properties and composition of ordinary cast iron, mild steel scrap, and semi-steel are discussed. The author has carried out a number of tests to ascertain whether semi-steel of similar analysis or of slightly purer composition has a real advantage over ordinary cylinder or liner iron. The extravagant claims of the semi-steel enthusiast are not borne out ; but such mixtures have their advantages, and their more common adoption should go some way towards solving the problem of obtaining suitable and consistent qualities of cast iron.

H. Field, *What is Semi-Steel?* (Paper read before the Institution

of British Foundrymen: Foundry Trade Journal, March 3, 1921, vol. 23, pp. 201-204). The manufacture, treatment, and properties of semi-steel are discussed.

Y. A. Dyer, *A Specification for Cupola Semi-Steel* (Iron Age, January 6, 1921, vol. 107, pp. 9-10, 104). The control of mixtures, and the percentages of steel scrap to be used for various classes of products, are discussed.

Centrifugal Casting.—J. E. Hurst, *Notes on Centrifugal Castings* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, May 5, 1921, vol. 23, pp. 400-401). The advantages of the centrifugal process is outlined and the properties of the castings discussed.

G. K. Burgess, *Tests of Centrifugally Cast Steel* (Iron Age, March 24, 1921, vol. 107, pp. 764-766). The results are given of a number of tests carried out on several hollow steel cylinders cast by the Mill-spaugh centrifugal process.

Special Castings.—H. Cole Estep, *Manufacture of Rail-Chairs in English Foundries* (Foundry, September 1920, vol. 48, pp. 696-700). The installation of moulding machines and for the preparation and conveyance of sand at the foundry of Smith-Patterson & Co., Ltd., Blaydon on Tyne, is described, with an account of the operations involved in moulding and casting railway chairs.

P. Dwyer, *Problems Encountered in Gas-Engine Castings* (Foundry, 1920, vol. 48, pp. 980-983). A description is given of the practice at the plant of the Rathburn Jones Engineering Co., Toledo, Ohio. Nearly all the castings are poured in dry sand. To facilitate drying of the moulds, the drags of all flasks are provided with bars, and bottom plates are dispensed with. All cores are given at least one coating of black wash, known as silver lead. Charcoal iron is employed in the charge for castings subjected to a pressure test in order to promote high density and also to prevent segregation in castings containing sections of uneven thickness. The steel scrap used in making semi-steel consists principally of old rails and fish plates. For ordinary iron castings which do not have to stand a pressure test, the metal is poured from a mixture of approximately 1000 lbs. of pig iron and 600 lbs. of scrap.

F. Holberry, *Making Castings for Rolling-Mill Construction* (Presidential Address before the Institution of British Foundrymen, October 2, 1920: Foundry Trades Review, November 1920, vol. 22, pp. 847-850). The author describes the manufacture of cast iron rolls, and the production of castings for rolling-mill parts.

The Manufacture of Moulding Boxes (Foundry Trade Journal, November 1920, vol. 22, pp. 868-869). Particulars are given of the operations involved in the manufacture of steel flasks or moulding

boxes which are used in the production of castings for automobile parts.

E. Polushkin, *Chilled Cast Iron Wheels* (Revue de Métallurgie, Mémoires, Nov., Dec., 1920, vol. 17, pp. 713-735, 785-802; January 1921, vol. 18, pp. 43-57). The method of casting wheels with chilled tread and the composition of the metal are described.

Foundry Sands.—C. P. Karr, *Standardisation of Moulding Sands* (Iron Age, September 30, 1920, vol. 106, pp. 846-849). The desirability of a standard in terms of which moulding-sand properties can be expressed, is dealt with. For fineness the Scranton and Parmelee methods are suitable, and a new form of permeability apparatus is described for tests. Other physical properties of moulding sand are described.

H. B. Hanley and H. R. Simonds, *Testing of Foundry Sands* (Foundry: Foundry Trade Journal, November 1920, vol. 22, p. 879). The main characteristics of various foundry sands are discussed and the method for determining their relative value in different sands are given.

R. L. Lindstrom, *Obtaining Moulding Materials for the Steel Foundry* (Paper read before the American Foundrymen's Association, October 1920). The author gives the results of tests on the properties of sands and facings for steel foundry purposes.

Moulding and Core-Making.—H. Cole Estep, *Notes on European Moulding Machines* (Paper read before the American Foundrymen's Association, October 1920). Various types of British, French, and German machines are described and illustrated.

R. J. Doty, *Some Details in the Moulding of Small Steel Castings* (Paper read before the American Foundrymen's Association, October 1920).

E. Touceda, *Thacher Moulding Process for Propeller Wheels and Blades* (Paper to be read before the American Institute of Mining and Metallurgical Engineers, September 1921).

J. Horner, *Runners and Risers* (Foundry Trade Journal, December 1920, vol. 22, pp. 938-941). A discussion of the methods of pouring castings, and the conditions governing the location of runners and ingates.

S. Corden, *General Core-Making* (Paper read before the Institution of British Foundrymen, October 1920: Foundry Trade Journal, January 6, 1921, vol. 23, pp. 8-11). The latest developments in core-making are dealt with.

J. L. Jones, *Core-Baking in Electrically Heated Ovens* (Paper read before the American Foundrymen's Association, October 1920: Iron Age, November 25, 1920, vol. 106, pp. 1385-1387). A description is given of the use of the Westinghouse thermostat for controlling the temperature in core-ovens.

The Application of Electrical Heating to Industrial Purposes (Iron and Coal Trades Review, October 8, 1920, vol. 101, pp. 473-474). Particulars are given of the electrical heating appliances developed by the Ateliers de Construction Oerlikon of Switzerland. These include an apparatus for the production of hot air, which has found a wide field of application in foundries for the drying of moulds.

Cleaning Castings.—F. W. Wilson, *Cleaning and Dressing Castings* (Paper read before the Manchester Association of Engineers: Foundry Trade Journal, March 17, 1921, vol. 23, pp. 243-246). The use of tumbling barrels, abrasives, and sand-blasting plant is discussed.

Air Furnaces.—H. E. Diller, *Air-Furnace Iron for Big Castings* (Foundry, 1920, vol. 48, pp. 973-977). The author describes one of the foundries of the Westinghouse Electric and Manufacturing Co., at Lester, Pennsylvania, which is equipped with two 40-ton and one 15-ton air furnaces, in addition to four cupolas. The plant and methods of operation are described in detail.

Malleable Castings.—F. H. Hurren, *Experiments in Malleable Iron* (Lecture before the Institution of British Foundrymen: Foundry Trade Journal, February 10, 1921, vol. 23, pp. 125-128). The author gives the results of a number of investigations on the composition and physical properties of malleable cast iron.

E. Touceda, *Malleable Castings* (Mechanical Engineering, August 1920, vol. 42, pp. 431-432). Malleable castings can now be produced having an ultimate strength of 22 tons per square inch and an elongation 12·5 per cent. In view of these conditions malleable castings can advantageously replace grey iron castings and steel castings for many purposes. Malleable castings are fine-grained and invariably free from internal strains and blowholes, and have superior rust-resisting capacity.

E. Touceda, *Progress in Manufacture of Malleable Iron* (Paper read before the American Foundrymen's Association, October 1920). The author refers to the improvements made in the production of malleable iron in recent years, and discusses the possibility of further developments.

R. Stotz, *American Malleable Castings compared with German* (Giesserei Zeitung, October 1, November 1, 15, 1920, vol. 17, pp. 305-309, 356-359, 373-377).

H. A. Schwartz, *American Malleable Cast Iron* (Iron Trade Review, December 2, 1920; January 20, 1921; February 3, 17; March 3, 17, 31; April 14, 28; vol. 67, pp. 1536-1540; vol. 68, pp. 213-218, 353-357, 361, 485-488, 490, 628-631, 633-634, 770-775, 901-904, 1038-1042, 1175-1180). A series of articles dealing extensively with the development of the malleable cast iron industry, modern methods

of manufacture, metallurgical principles involved, and the properties of malleable cast iron.

H. A. Schwartz, *The Triplex Process for Making Electric Furnace Malleable* (Paper read before the American Foundrymen's Association, 1920). The author describes the Kranz process, which involves the use of the cupola, Bessemer converter, and electric furnace.

Foundry Equipment.—*Briquetting Press for Cast-Iron Turnings* (Engineering, November 12, 1920, vol. 110, p. 638). An illustrated description of the Boreas press is given. The appliance is suitable for use in works having machine shops and foundries; it is capable of turning out 120 to 150 briquettes an hour, the average weight of a briquette being about $6\frac{1}{2}$ lbs. The mixture is composed of cast-iron turnings with 5 per cent. of slaked lime and 5 per cent. of water.

J. L. Wilson, *Foundry Equipment in Modern Plants* (Paper read before the National Founders' Association, New York, November 18, 1920: Iron Age, November 25, 1920, vol. 106, pp. 1392-1397). The author deals with labour-saving equipment and discusses the economical working of foundries.

E. A. Hunger, *Labour-Saving Foundry Innovations Planned* (Iron Age, October 21, 1920, vol. 106, pp. 1031-1035). An illustrated description of the Lycoming Motors Corporation plant at Williamsport, Pennsylvania, and of the Carousel and Apron conveyer and monorail system appliances installed to diminish labour costs. Special features of core-oven room ventilation and of sand-blast methods are also described. Four large Whiting continuous melting cupolas, two of 96 inches diameter and two of 84 inches diameter, are employed, and the continuous circular pouring tables or carousels embody a number of novel features.

PRODUCTION OF STEEL.

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I.—PROCESSES OF STEEL PRODUCTION.

Steel-Furnace Construction.—H. Spence Thomas, *The McKune Open-Hearth Port for Coke-Oven Gas* (Iron and Coal Trades Review, February 4, 1921, vol. 102, p. 162). The McKune port is primarily designed for burning debenzolised coke-oven gas in the open-hearth furnace. The air enters from the regenerator passing up a central vertical uptake into the main port, and the gas is led through pipes entering at each side of the port, the arrangement being the same at both ends of the furnace. Gas pressure is controlled by a governor, the pressure at the furnace being about 10 oz. per square inch. The air meets the gas in the port and complete combustion takes place throughout its length, the products passing over the bath. Two vertical downtakes are arranged at each end, one on either side of the central air uptake, and these are fitted with dampers which are closed to the main port when air is being admitted and are opened at the other end where the products of combustion are passing out, this arrangement being provided to accommodate the larger volume of burnt gases. On reversing the furnace these dampers are automatically reversed at the same time. Sectional drawings show the arrangement and operating gear.

New Methods of Burning Fuel (Iron Trade Review, January 6, 1921, vol. 68, pp. 20–22). An illustrated description of the McKune system for burning coke-oven gas in open-hearth furnaces.

H. F. Miller, *Design of Ports for Open-Hearth Furnaces* (Blast-Furnace and Steel Plant, November 1920, vol. 8, pp. 612–614). Two types of circular water-cooled ports are illustrated and described. The port consists of a hollow water-cooled flue, tubular in shape, which extends from the gas port into, but not entirely across, the air uptakes.

Air-Cooled Slag Pockets (Iron Age, April 7, 1921, vol. 107, p. 901). A description is given of a new type of removable air-cooled slag pocket, which permits ease of handling and saves labour.

Steel-Making Practice.—F. Thomas, *Modern Methods of Steel Production* (Stahl und Eisen, February 10, 17, 1921, vol. 41, pp. 185–193, 223–227). The metallurgical operations and reactions involved in working the duplex process are set out (1) in working with acid converter and basic open-hearth, (2) with basic mixer and basic open-hearth, and (3) with basic converter and basic open-hearth. The great importance of the slag conditions is emphasised. The quantity of the slag is of no less importance than its composition. It is therefore desirable constantly to study the relation between the slag and the melt, and formulas are given which serve as a rough-and-ready means for checking the progress of the reactions in the bath.

J. H. Hall and G. R. Hank, *Electric versus Converter Steel* (Foundry, 1920, vol. 48, pp. 115–116). An electric furnace and a converter, each of 3-ton capacity, were operated under identical conditions. Castings from the converter showed numerous hot cracks, these being in nowise proportional to the sulphur content. Steel of the same analysis from the electric furnace was remarkably free from such defects. A table is given of a number of converter and electric furnace heats showing the percentage of impurities and number of cracked castings, indicating that though sulphur is a contributing cause, it does not have as great an effect in causing hot cracks as does the method of manufacture of the steel.

F. L. Toy, *The Basic Open-Hearth Process* (Paper before American Iron and Steel Institute, October 28, 1920). A general review of recent progress in basic open-hearth practice and furnace design.

G. A. V. Russell, *The Basic Open-Hearth Melting-Shop Equipment and Practice in England* (Blast-Furnace and Steel Plant, January, March, 1921, vol. 9, pp. 31, 38–45, 213–217). A general description of the mixer plant and mixer practice, dealing also with the design of melting furnaces and metallurgical operations.

G. A. V. Russell, *Basic Open-Hearth Melting-Shop Equipment and Practice* (Paper read before the Swindon Engineering Society: Iron and Coal Trades Review, January 14, 21, 28; February 11, 18, 1921, vol. 102, pp. 37–39, 82–84, 122–124, 204–206, 238–239). The author gives an illustrated account of the plant and methods used in modern steelworks in this country for the production of steel by the basic open-hearth process, and indicates some of the means which have been developed for accelerating the output and improving the quality of such steel under the different operating and economic conditions met with in various steel-making centres.

L. Blum, *Influence of the Basicity of the Slag on the Working Results of the Basic Bessemer Converter* (Stahl und Eisen, January 20, 1921, vol. 41, pp. 69–74).

E. A. Wheaton, *Use of High Manganese Iron in Basic Open-Hearth Practice* (Paper before American Iron and Steel Institute, October 22, 1920: Blast-Furnace and Steel Plant, November 1920, vol. 8, pp. 596–598). To meet the difficulty due to high sulphur in pig iron

resulting from the enforced use of high sulphur fuel, it is recommended to increase the manganese in the pig iron. The records of the Bethlehem plant show that pig iron containing 1.7 to 2.1 per cent. manganese improves the quality of the open-hearth steel without reduction of tonnage.

E. Killing, *The Effective Use of Manganese in the Basic Open-Hearth* (Stahl und Eisen, November 18, 1920, vol. 40, pp. 1545-1547). The conditions necessary to secure the most effective use of the manganese additions are found by practical experiment to be the following: The charge should be tapped at the moment of maximum reduction of manganese from the slag. The manganese addition should be kept low, not above 1.6 to 1.8 per cent. The bases should be added in such quantities as neither to exceed nor fall short of the capacity of the slag for absorption. An excess of bases with a high manganese addition is particularly harmful. Silicon, silica, phosphorus, the substances taking up lime, should be added in as small quantities as possible. The charge should be worked at as high a temperature as possible, and the manganese added in metallic form.

J. Puppe, *Practice with the Maerz Furnace* (Stahl und Eisen, November 25-December 2, 9-16, 1920, vol. 40, pp. 1592-1599, 1648-1656). A description with sectional drawings is given of the open-hearth furnace constructed by the Maerz Company of Breslau, which has been in operation at the works of the Freistädter Iron and Steel Company at Freistädt, in Austrian Silesia, since 1913. The distinctive feature of the furnace lies in the arrangement of the air uptakes and ports. Two air uptakes are carried up vertically from the roof of the regenerator, and the ports open out one on each side of the gas port and just in front of it, the latter being built out free of the furnace with a downward inclination of 10°. The absence of any bends or angles in the air passages simplifies the whole construction of the furnace ends and facilitates the inflow of air. Four such furnaces are now in operation of about 30 tons capacity each. The principal dimensions of the two latest are: Length of hearth, 7000 millimetres; width inside of furnace walls, 3200 millimetres; depth of bath, 500 millimetres; height of crown above bath, 1700 millimetres. The average number of heats obtained during one run is 560. The initial construction of the furnace is less than that of the ordinary type, and repairs when the furnace is laid off can be accomplished in about three-fifths of the time otherwise required.

H. Czirn-Terpitz, *Practice with the Maerz Furnace* (Stahl und Eisen, March 31, 1921, vol. 41, pp. 444-446). The working of a 35-ton Maerz furnace is described. The furnace was installed at the Hubertushütte in December 1918, and considerable economies in refractory material and labour, with high output, are said to have been achieved.

W. J. Beck, *The Development of Commercially Pure Iron in the Basic Open-Hearth Furnace* (Paper read before the American Iron and Steel Institute, May 27, 1921). An account is given of the process

of manufacture of ingot iron at the steelworks of the American Rolling Mill Company.

S. Schleicher, *Use of Fluorspar in the Open-Hearth* (Stahl und Eisen, March 17, 1921, vol. 41, pp. 357-361). When fluorspar is added to an open-hearth slag, the fluorspar is decomposed only up to a certain limit, which is found to be in the neighbourhood of 2 to 2.5 per cent. calcium fluoride. On first adding fluorspar silica passes off from the slag in the form of silicon fluoride, but this is replaced by silica from the furnace lining. Sulphur is driven off from the slag in some form of vapour, and the slag then takes up more sulphur from the bath. Since fluorspar almost entirely destroys the citric solubility of the phosphoric acid, fluorspar cannot be used as an addition to slags which are valuable as manure on account of their richness in phosphoric acid.

H. D. Hibbard, *Reversion of Phosphorus to Basic Steel in the Ladle* (Blast-Furnace and Steel Plant, December 1920, vol. 8, pp. 642-643). The fundamental cause of the reversion of phosphorus is the presence in the steel of reducing elements added to give the composition desired, aided usually by the entrance into the slag of silica taken up from the ladle lining. The conditions upon which phosphorus is likely to revert from the slag to the steel are discussed.

J. R. Cain, *New Deoxidisers for Steel Manufacture* (Chemical and Metallurgical Engineering, November 3, 1920, vol. 23, pp. 879-882). The results are given of an investigation carried out at the Bureau of Standards on the function and action of deoxidisers. The investigation was limited to work on oxides of the more commonly used deoxidising elements—manganese, silicon, aluminium, and titanium. Seventy-three deoxidising alloys are shown, by means of tables, to have melting points when oxidised somewhat below the melting point of pure iron. The only basis the investigation furnishes for judging the relative merits of the deoxidisers is comparative fusing points of the slags. It may be expected that a deoxidiser which gives the deoxidation slag of lowest fusing point will be the best. Of the new oxidisers the most fusible are as follows :

Composition.						Melting Point. Mixed Oxides. Degrees C.
75 per cent. Mn,	24 per cent. Si	.	.	.	.	1228
41 "	Mn, 59 "	"	Ti	.	.	1160
49 "	Mn, 18 "	"	Ti, 33 per cent. Si	.	.	1130
13 "	Al, 52 "	"	Mn, 35 "	Si	.	1121
12 "	Al, 47 "	"	Mn, 41 "	Ti	.	1320

H. D. Hibbard, *Gases Obtained in Molten Steel* (Blast-Furnace and Steel Plant, January, February, March, 1921, vol. 9, pp. 51-53, 139-140, 193-195, 197). The nature and formation of gases in molten steel are considered.

P. Rosin, *Principles of the Heat Losses in Metallurgical Furnaces* (Metall und Erz, November 8, 1920, vol. 17, pp. 463-475). The

factors governing the heat losses of furnaces due to conduction and radiation are discussed from a mathematical point of view.

Manufacture of Alloy Steels.—Pokorny, *Manufacture of Molybdenum Steel* (Zeitschrift für Metallkunde, 1920, vol. 12, pp. 238–239). Molybdenum is readily oxidised on being added to steel, and the oxide being very soluble, the best method of manufacturing molybdenum steel is to use an alloy containing about 45 per cent. molybdenum which has been melted electrically and thoroughly deoxidised. Titanium and vanadium are the best deoxidisers for such steels, as they readily take up nitrogen and their nitrides are easily volatilised. When aluminium and silicon are used, nitrides of molybdenum form which volatilise with difficulty. The double iron-molybdenum carbide is scarcely soluble in iron. It is therefore advisable to add the required amount of a low-carbon ferro-molybdenum to a bath low in carbon and then to recarburise to the desired amount.

R. W. Leonard, *Nickel-Copper Steel* (Transactions of the Engineering Institute of Canada, 1918, vol. 32, Part 2, pp. 361–383). The author describes experiments in the manufacture of nickel-copper steel direct from the Sudbury ores. The ores as received contained 46 per cent. iron, 1·35 per cent. nickel, and 25 per cent. copper. They were treated in electric furnaces, and about 70 tons of steel containing 2½ per cent. nickel and copper combined were produced. Later the Nicu Steel Corporation took up the manufacture and a product containing 3½ per cent. of nickel and copper was obtained; analyses and results of tests of Nicu steel are given.

A New Alloy Steel (Iron Trade Review, April 7, 1921, vol. 68, pp. 974–975). Particulars are given of the manufacture and uses of a new alloy known as burrowite. The alloy is made from nickelifercous ore obtained from the Sudbury district of Ontario. An analysis of the alloy is as follows: Silicon, 2·51; iron, 52·89; nickel, 3·98; manganese, 0·046; sulphur, 1·90; cobalt, 0·15; arsenic, 0·11; copper, 0·59; phosphorus, 0·12; tungsten, 0·24; and chromium, 2·61 per cent. It is stated that the alloy gives steel the property of machinability even when showing qualities of extreme hardness. The results are given of tests showing the properties of steel containing 1, 1·5, and 2 per cent. of the alloy.

F. Peters, *Progress in the Electro-Metallurgy of the Alloy Metals since 1915* (Glückauf, September 25; October 2, 9, 16, 23; November 6, 1920, pp. 761–769, 793–797, 810–817, 835–840, 863–868, 906–908). A general review of the literature of the past years on the electro-metallurgy of the principal metals used for alloying with steel. The following metals and their steel alloys and compounds are dealt with: nickel, cobalt, manganese, vanadium, silicon, titanium, uranium, tungsten, molybdenum.

Electric Steel Furnace Practice.—W. S. Gifford, *The Present Position and Prospects of Electric Steel in Great Britain* (Electrician, November 5,

1920, vol. 85, pp. 528-529). A consideration of the altered circumstances due to the change over since the war. Incidentally, the manufacture of stainless steel and other steel alloys in the electric furnace, and the scrap problem so far as it affects the prospects of electric steel, are discussed. The manufacture of acid electric steel has not been as widely developed in Great Britain as in America, although where good scrap is available its use would be advantageous.

R. M. Keeney, *The Present Status of the Electric Furnace in the American Metal Industries* (Paper read before the National Electric Light Association: Chemical and Metallurgical Engineering, November 17, 1920, vol. 23, pp. 980-984). The present technology and future possibilities of the electric furnace as applied in the manufacture of synthetic cast iron, steel, and ferro-alloys, and in heat treating and the smelting of non-ferrous ores are considered.

J. W. Galvin and C. N. Ring, *Making Acid Electric Steel* (Transactions of the American Foundrymen's Association, October 1920, vol. 67, pp. 1130-1132). In discussing the problems encountered in acid electric furnace practice, the author describes methods for controlling the silicon content of the finished product and the oxidation of the charge.

W. E. Cahill, *Electric Furnace Practice at Treadwell* (Mining and Scientific Press, April 16, 1921, vol. 122, pp. 535-537). Steel-making practice with an Heroult furnace at the plant of the Alaska Treadwell Gold-mining Co. is described.

C. Hering, *Electrodynamic Forces in Electric Furnaces* (Paper read before the American Electrochemical Society, April 1921). A number of recently discovered mechanical forces are described, which are of electric origin and which may be made use of, or may be detrimental, in some types of electric furnaces, chiefly those in which the heat-developing resistor is a liquid, which responds to these forces more readily than a solid. Such forces may be usefully applied to cause the liquid metal to flow very rapidly through the heat-developing resistor, thereby enabling the furnace to be forced, and to cause a strong upward circulation in an adjoining bath, by which the metal is refined. After referring briefly to the "pinch effect," the author gives a description of the "stretch effect" and of the "corner effect," known also as the "motor effect."

C. Reed, *Direct Current used for Furnace* (Foundry, 1920, vol. 48, pp. 775). The application of direct current for steel melting is discussed. For good working it is important to start with a hot charge. No greater amounts of ferro-silicon and aluminium are required than in alternating-current working.

A. M. Kuhlmann and A. D. Spillman, *Determining Heat in Electric Steel* (Paper read before the American Electrochemical Society, September-October 1920: Iron Trade Review, December 2, 1920, vol. 67, p. 1546). The authors have made a number of calorimetric determinations of the heat content of liquid slag and liquid steel produced in a 6-ton Heroult furnace. It is estimated that the heat

content of liquid steel from an electric furnace is 325 calories at a temperature of 1900° C., this figure being considered probably the maximum for this temperature.

C. H. Booth, *Securing Long-Lived Furnace Linings* (Paper read before the Electric Furnace Association, October 6, 1920 : Iron Trade Review, December 23, 1920, vol. 67, pp. 1745).

W. G. Mylius, *The Regulation of Electric Steel Arc Furnaces using Movable Electrodes* (Paper read before the American Electrochemical Society, April 1921). The author discusses the difficulties of operating arc furnaces, particularly when melting cold scrap, and the kinds of arc current regulators which have been devised to maintain some function of the power input constant, such as current, voltage, watts, or a combination of these. A new form of electrode regulator is described and illustrated which will operate with greater precision and at higher speeds than previous types, and thus overcome the difficulties of "hunting," the phenomena of which are explained.

M. R. Wolfe and V. de Wysocki, *Measuring Furnace Electrode Losses* (Paper read before the American Electrochemical Society, September-October 1920 : Iron Trade Review, December 16, 1920, vol. 67, pp. 1679-1680). The authors, after an investigation of a 6-ton Heroult furnace, arrive at the conclusion that although a small amount of heat is radiated from the electrode between the upper and lower cooling bands, this heat is negligible in comparison with the heat carried away by the cooling water.

F. Hodgson, *Heat Losses in Electric Steel Furnaces* (Iron Age, November 11, 1920, vol. 106, pp. 1262-1263 ; Electric Review, 1920, vol. 77, pp. 726-728). The causes of electrode heat loss are faulty joints or defective electrodes, imperfect contact, pencilling off of the electrode at the point of arc, and the combining of oxygen with the carbon of the electrode and the resultant burning of the electrode. Pencilling of electrodes is probably the indirect cause of more heat losses than any other cause. To overcome this the Brooke electrode economiser, a type of electrode cooling ring, has been developed.

E. T. Moore, *Operating Details of Electric Furnaces* (Chemical and Metallurgical Engineering, January 26, 1921, vol. 24, pp. 171-176). An excerpt from a report of the Electric Furnace Committee of the Association of Iron and Steel Electrical Engineers, based on a *questionnaire* submitted to steel manufacturers operating electric furnaces.

Electrodes.—J. W. Richards, *The Söderberg Self-Baking Continuous Electrode* (Paper before American Electrochemical Society, April 10, 1920 : Transactions, vol. 37). The continuous electrode, invented by C. W. Söderberg, was devised to obviate the necessity of changing or renewing electrodes during the operation of electric furnaces. The electrode is enclosed in an iron casing into which raw electrode mixture is rammed periodically as the lower end burns away, the new mass

becoming baked by the heat of the furnace as it gradually descends. The electrode holder encircles the casing, which must be heavy enough to carry the current past the unbaked mass to the baked and conducting part of the electrode. The stamping in of the new material is done from a platform above the furnace, either by hand or compressed-air hammers.

R. Durrer, *The Söderberg Continuous Electrode* (Stahl und Eisen, November 25-December 2, 1920, vol. 40, pp. 1599-1603). The making of the electrode, with results in practical operation, is described.

Electric Furnaces of Special Type.—E. F. Russ, *A New Electric Arc Furnace* (Giesserei Zeitung, January 1, 1921, vol. 18, pp. 3-5). A short description of a new design of electric arc furnace for small foundry work. The distinctive feature lies in the form of the electrode, the lower end of which is enlarged inside the furnace and takes the shape of an adjustable piston, forming a roof to the bath, the bottom of the bath being similarly formed by a bottom electrode. The effect of this is to prevent the creeping upwards of the electric arc, which occurs in the more usual form of electrode, while the heat generated is retained in the bath through the checking of the radiation towards the furnace crown. The life of the roof is thereby greatly increased.

R. D. Thomas, *Moore Rapid "Lectromelt" Furnace* (Journal of the American Institute of Electrical Engineers, 1920, vol. 39, pp. 1038-1039). The advantage of the electric furnace over the open-hearth furnace for steel melting is discussed, and the features of the Moore furnace are described.

E. F. Northrup, *High-Frequency Induction Steel Furnace* (Chemical and Metallurgical Engineering, February 16, 1921, vol. 24, pp. 309-311). The furnace is designed for operation with high-frequency current, and consists of only two essential parts—the induction coil and a conical-shaped crucible. The latter fits within the induction coil. The crucible is designed to hold about 60 lbs. of metal.

G. H. Clamer, *The Induction Electric Furnace* (Journal of the Franklin Institute, October 1920, vol. 190, pp. 473-507). The author deals with the principle on which the induction furnace operates, and traces its development from the time of its invention by E. A. Colby about 1888 down to the present. The designs and improvements effected by different inventions are touched on, and an illustrated description is given of the Ajax-Wyatt induction furnace as designed for use in brass foundries.

Repelling Arc Furnace (Electrical World, 1920, vol. 76, p. 809). Brief particulars are given of an arc furnace with a new system of operation. The electrodes are balanced so that they hang together when the current is off. The arc is formed by the mutually repelling force when the current flows in the electrodes. The extent of this action is regulated by balance weights on the electrodes.

E. T. Moore, *An Improved Greaves-Etchells Electric Furnace Installation* (Chemical and Metallurgical Engineering, October 27, 1920, vol. 23, pp. 825-832). An illustrated description of the Greaves-Etchells electric furnace and of the arrangement of the electrical equipment as installed at the plant of the Halcomb Steel Co., together with a record of operations.

F. W. Brooke, *The Greaves-Etchells Furnace* (Journal of the American Institute of Electrical Engineers, 1920, vol. 39, pp. 1036-1038).

S. H. Ourbacker, *Weeks' Electric Furnace* (Journal of the American Institute of Electrical Engineers, 1920, vol. 39, pp. 1039-1040).

J. B. C. Kershaw, *English and American Types of Electric Iron and Steel Furnaces Compared* (Iron and Coal Trades Review, November 12, 1920, vol. 101, pp. 638-640). An illustrated description is given of the following types of furnaces: Booth-Hall, Girod, Greaves-Etchells, Grönwall-Dixon, Heroult, Ludlum, Rennerfelt, Snyder, Vom Bauer, and Webb furnaces.

Electric Furnace for High-Speed Steel (Iron Age, March 17, 1921, vol. 107, pp. 691-692). A description of the Newkirk furnace. It has three 6-inch graphite electrodes entering through the roof, and a bottom electrode consisting of a copper plate covered with the refractory lining.

Statistics of Electric Steel Furnaces.—E. F. Cone, *The Status of the Electric Steel Industry* (Iron Age, January 6, 1921, vol. 107, pp. 69-71). Tables are given showing the number, the size, and product of each type of electric furnace in the United States and Canada. At the end of 1920 there were 356 electric furnaces in the United States and 43 in Canada.

New Steelworks.—*Extensions to the South Bank Works of Messrs. Bolckow, Vaughan & Co., Ltd.* (Iron and Coal Trades Review, February 4, 1921, vol. 102, pp. 151-155). The melting shop contains eight 60 to 70-ton basic open-hearth furnaces, which are disposed four on either side of two 400-ton mixers. A battery of thirty producers supply gas to the furnaces and mixers. A Babcock and Willcox waste-heat boiler is installed in connection with each furnace. The soaking pits comprise six nests of six holes, each hole taking four ingots. The rolling-mill plant consists of a 40-inch cogging mill, an 18-inch merchant mill, and a 36-inch three-high plate mill.

Redcar Steel Works and Rolling-Mills (Iron and Coal Trades Review, October 8, 1920, vol. 101, pp. 471-472). Particulars are given of the layout of the steel plant of the Warrenby Works of Dorman, Long & Co., Ltd. The equipment includes a 400-ton mixer, six 60 to 70-ton stationary open-hearth furnaces, and four 80-ton tilting furnaces. The exhaust gases from the mixer and furnaces are used under boilers.

The cogging mill, with rolls 44 inches in diameter by 10 feet 6 inches long, is one of the largest of its type in this country.

J. Horton, *Baldwins, Ltd., adds New Steel Plant* (Iron Trade Review, October 21, 1920, vol. 67, pp. 1133-1138). An illustrated description of the new steelworks of Baldwins, Ltd., at Margam, South Wales.

Blaenavon Iron and Steel Works (Iron and Coal Trades Review, October 22, 1920, vol. 101, pp. 541-544). The steel-making plant consists of six 40-ton and one 50-ton acid open-hearth furnaces. Four 50-ton gas-fired soaking pits are provided. The rolling-mills consist of a 32-inch cogging mill, a 26-inch roughing and finishing bar mill, and a tyre mill.

C. H. Hunt, *New Steel Plant of the Weirton Steel Co.* (Iron Age, March 10, 1921, vol. 107, pp. 619-627; Iron Trade Review, March 10, 1921, vol. 68, pp. 685-691). The layout of this plant, which is situated in West Virginia, is described and illustrated. It includes a 1300-ton mixer and seven 120-ton open-hearth furnaces. A waste heat boiler is installed at each furnace.

Steel Plant Operated with Waste Heat (Iron Age, September 23, 1920, vol. 106, pp. 765-769). The new works of the Electric Steel and Forge Co., Cleveland, Ohio, for the manufacture of alloy steels, are illustrated and described. In this plant the whole of the steam requirements of the hammer and press shops are generated from the waste heat of the furnaces, which are provided with waste heat boilers embodying certain special and novel designs.

Mexican Plant undergoes Rehabilitation (Iron Age, December 30, 1920, vol. 106, pp. 1723-1726). Brief particulars are given of the plant of the Monterey Iron and Steel Co., Mexico.

Japanese Iron and Steel Works (Iron Age, October 21, 1920, vol. 106, pp. 1045-1047). A review of recent developments in the Japanese iron and steel industry is given, with a brief description of the plant at the principal government and private works, and estimates of their productive capacity.

L. P. Sidney gives a similar review, *Vulcan in Nippon* (Times Trade Supplement, April 16, 1921, pp. 16-17), with additional details relative to Japan's iron ore and coal resources and the development of the iron and steel industry during the last decade.

Steelworks Equipment.—A. A. Rackoff, *Process and Apparatus for Increasing Production in Steel Manufacture* (Blast-Furnace and Steel Plant, December 1920, vol. 8, pp. 645-651). The teeming of the charge is facilitated by a new type of ladle crane and an improved design of ladle.

F. A. Hooper, *Electric Lifting Magnets* (Paper read before the Staffordshire Iron and Steel Institute: Iron and Coal Trades Review, February 25, 1921, vol. 102, p. 278). The design and construction of lifting magnets, and their application to iron and steel works, are discussed.

Costs of Steel Making.—E. H. Ballard, *Comparing Costs of Steel Making* (Foundry, 1920, vol. 48, pp. 697–698). Costs of operation during four months of a 20-ton acid open-hearth furnace and a 6-ton basic electric furnace are compared. The cost of production of steel in the electric furnace is great, but this process is considered to be superior and the additional cost is not regarded as prohibitive.

Sir R. Hadfield, *Costs of Steel Melting* (Presidential Address to the British Commercial Gas Association: Iron and Coal Trades Review, October 22, 1920, vol. 101, p. 548). A table is submitted giving a comparison of the cost of heating and melting iron and steel by coal, gas, and electricity.

P. M. Tyler, *High-Speed Steel Manufacture in Sheffield* (Iron Age, February 10, 1921, vol. 107, pp. 371–374). The present practice, costs, prices, and the sources of raw material are dealt with.

History of Steel.—A. Sauveur, *Steel Wizards, Past and Present* (Chemical and Metallurgical Engineering, September 29, 1920, vol. 23, pp. 633–635). A brief account of the contribution of American scientists to recent developments in the manufacture of steel.

Basic Slag.—E. J. Russell, *The Utilisation of Basic Slag* (Paper read before the Faraday Society: Chemical News, February 28, 1921, vol. 122, pp. 73–75). The use of basic slag for agricultural purposes is dealt with.

C. H. Desch, *The Physical Chemistry of Basic Slags* (Paper read before the Faraday Society: Chemical News, March 4, 1921, vol. 122, pp. 102–103).

II.—CASTING AND TREATMENT OF INGOTS.

Production of Sound Steel.—G. Niemkof, *Reduction of the Pipe in Bottom-Poured Ingots* (Revue de Métallurgie, Mémoires, December 1920, vol. 17, pp. 842–844). In order to diminish the formation of the pipe in large bottom-poured ingots, a mould of special design was used. The wall at the bottom part was made extra thick; at the middle part, a hollow space was provided in the wall all round the mould and filled with non-conducting material, the inner part of the wall at this point being kept rather thin. The top part of the mould was lined with refractory material in the ordinary way. The mass of metal in the ingot is by this means kept liquid in the centre for a longer period, and feeds the lower part as it shrinks in cooling.

G. K. Burgess, *Steel Rails from Sink-Head and Ordinary Rail Ingots* (Chemical and Metallurgical Engineering, November 10, 17, 24, 1920, vol. 23, pp. 921–925, 969–975, 1017–1022). An effective study has been made of the suitability of ingots produced by the Hadfield sink-head process for the manufacture of rails, and of ordinary rail steel

ingots rolled at the same time and under as nearly identical conditions as possible in the same mill. The sink-head ingots are shown to give much more uniform metal than the ordinary American types. Detailed results of the physical tests are given.

E. Gathmann, *Casting and Moulding Steel Ingots* (Paper read before the American Institute of Mining and Metallurgical Engineers, August 1920). Defects in ingots and developments in the production of sound steel are discussed.

A. B. Wilson, *Defects in Steel Originating in the Ingot* (Chemical and Metallurgical Engineering, December 15, 22, 1920, vol. 23, pp. 1161-1166, 1209-1213). The author deals with those defects in steel, as they appear under microscopic examination, which originate in the pouring and solidification of a steel ingot. Photomicrographs are given showing the nature of defects due to the treatment of the steel during the process of manufacture.

E. Kothny, *Influence of Deoxidation and the Period of Solidification on the Quality of Electric Nickel-Chrome Steel* (Stahl und Eisen, January 8, 1920, vol. 40, pp. 41-45).

E. Kothny, *Conditions for the Manufacture of Nickel-Chrome Steel for Aero-Crankshafts* (Stahl und Eisen, May 20, 1920, vol. 40, pp. 677-684). Furnace practice in the production of high-class nickel-chrome steel for shafts is described. To obtain a tough fibrous structure it is desirable to work with two oxidising slags. The influence of the additions, pouring conditions, and length of time of solidification is discussed.

H. D. Newell, *Segregation in Bars for Steel Tubing* (Chemical and Metallurgical Engineering, October 13, 1920, vol. 23, pp. 745-746). The author finds that the addition of aluminium in the ladle tends to reduce immediately the amount and depth of segregation.

Inclusions.—M. Matveieff, *Metallographic Methods for Studying the Nature of Non-Metallic Inclusions in Iron and Steel* (Revue de Métallurgie, Mémoires, Nov. 1920, vol. 17, pp. 736-752). For determining the constituents of non-metallic inclusions the best results were obtained by the use of 0.2 per cent. oxalic acid (20 to 30 seconds). This reagent attacks the sulphide inclusions but does not affect the polished surface of the specimen. The suitability of other reagents is also discussed.

A. A. Rackoff, *Improving Steel by New Pouring Method* (Iron Trade Review, December 9, 1920, vol. 67, pp. 1601-1602). The author has devised a new process for the production of clean steel. The ladle used has a perforated core which prevents solid particles from entering the ingot mould.

E. G. Mahin and E. H. Hartwig, *Inclusions and Ferrite Crystallisation in Iron and Steel* (Journal of Industrial and Engineering Chemistry, November 1920, vol. 12, pp. 1090-1095). The solubility of inclusions is discussed, and their influence in producing ferrite segregation.

E. G. Mahin and R. E. Brewer, *An Electrometric Method for Detecting Segregation of Dissolved Impurities in Steel* (Journal of Industrial and Engineering Chemistry, November 1920, vol. 12, pp. 1095-1098). A method has been developed for measuring the electrode potential of a single grain or microscopic point on a metal specimen. Results show lower values than when a pure metal is immersed in the usual way. No reason for this has been found, but fairly consistent values may be obtained on a given kind of material.

F. Wüst and N. Kirpach, *Determination of Slag in Steel* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1920, vol. 1, pp. 31-38).

Ingot Mould Design.—R. C. Woodward, *A Proposed New Ingot Mould for Steel* (Iron Age, January 27, 1921, vol. 107, pp. 262-263). The author discusses cracks in ingots, their causes, and the effect of heavy moulds, and outlines the advantages of a thin steel mould with water cooling.

FORGING AND ROLLING-MILL PRACTICE.

Theory of Furnace Design.—Groume-Grjmailo, *Theory of Furnaces based on the Laws of Hydrostatics* (Revue Universelle des Mines, April 15, 1921, vol. 9, pp. 132–144). A brief résumé is given of the theory of the application of the laws of hydrostatics to flames. The extracts are taken from the new edition of the author's work on that subject.

Forging Practice.—L. Aitchison, *Alloy Steels for Large Forgings* (Paper read before the Staffordshire Iron and Steel Institute, April 9, 1921). Of all the alloy steels which are suitable for the manufacture of large forgings, the following seem to be the most appropriate: (a) 3 per cent. nickel steel; (b) nickel-chromium steel with more than 4 per cent. of nickel and 1.1 per cent. of chromium; (c) nickel-chromium steels with from 3 to 4 per cent. of nickel and from 0.75 to 0.9 per cent. of chromium.

P. Rowley, *Some Troubles of a Drop-Forging* (Automobile Engineer, October 1920, vol. 10, pp. 412–416). The principal causes of defects in drop-forgings are illustrated and precautions for their avoidance are discussed, with notes on the selection and treatment of material for die-blocks.

Rolling-Mill Equipment.—*Three-High Plate Mill Plant* (Engineer, February 4, 1921, vol. 131, pp. 129–130). The new 36-inch three-high plate mill recently erected at the South Bank Works of Messrs Bolckow, Vaughan & Co., is illustrated and described. The mill was supplied by Davy Bros., Ltd., Sheffield.

G. R. Strate, *Electrical Equipment of a Large American Plate Mill* (Paper read before the Engineers Club of Philadelphia: Iron and Coal Trades Review, October 29, 1920, vol. 101, pp. 582–584). Particulars are given of the equipment of the 204-inch plate mill of the Lukens Steel Co., Coatsville, Pennsylvania.

G. L. Lacher, *Flexibility of Output assured in Scullin Mills* (Iron Age, March 31, 1921, vol. 107, pp. 829–837). The layout of the rolling-mill plant of the Scullin Steel Co. of St. Louis is described. The 22-inch mill is interesting from the standpoint of flexibility of output, as it may be employed either for the production of finished shapes or billets. The first of the four three-high stands is equipped with a floating middle roll, so that it may be used as a separate billet mill when desired.

C. H. Hunt, *Rolling-Mills of the Weirton Steel Co.* (Iron Age, March 17, 1921, vol. 107, pp. 693-702). This plant includes a 40-inch blooming mill and two Morgan continuous mills 21-inch and 18-inch for producing sheet bars, billets, and slabs.

B. M. Jones, *Motor-Driven Blooming Mill* (Iron Trade Review, February 17, 1921, vol. 68, pp. 491-493). The new electrical equipment for driving the 44-inch blooming mill at the Steelton plant of the Bethlehem Steel Corporation is illustrated and described.

J. D. Knox, *Drive is Feature of Sheet Mill* (Iron Trade Review, April 21, 1921, vol. 68, pp. 1099-1105, 1111). An illustrated description is given of the new rolling-mill plant of the Superior Sheet Steel Co., Canton, Ohio.

A New Wire-Rod Mill (Iron and Coal Trades Review, November 5, 1920, vol. 101, p. 618). Particulars are given of the layout of the wire-rod mill recently installed at the works of Richard Johnson and Nephew, Ltd., of Manchester. The mill is electrically driven and is of the continuous type. It is divided into a roughing train with ten stands, and two finishing trains each of seven stands.

New Mill to Roll Automobile Sheets (Iron Age, November 4, 1920, vol. 106, pp. 1181-1185). The layout of the new plant of the Newton Steel Co., Newton Falls, Ohio, for the production of steel sheets for automobiles is illustrated and described.

New Rolling-Mill for Alloy Steels (Iron Age, December 16, 1920, vol. 106, pp. 1597-1599). An illustrated description of the new five-stand, three-high 22-inch bar mill for rolling alloy steel billets and bars at the plant of the Pennsylvania Forge Co., Bridesburg, Philadelphia.

E. L. Shaner (Iron Trade Review, December 30, 1920, vol. 67, pp. 1805-1809, 1820). An illustrated description of the plant and methods employed at the new works of the Detroit Steel Tubes Co.

C. A. Ablett, *The Present Position of Electrically Driven Rolling-Mills* (Electrician, November 5, 1920, vol. 85, pp. 549-550). After referring to early attempts at electrical driving, a review of present progress is given, and the merits of direct *versus* alternating current are briefly discussed.

L. Rothera, *Notes on Rolling-Mill Drives* (*Ibid.*, pp. 514-517). A description of recent practice, in which the questions of available speed, increase in motor size, the driving of continuous mills, the relative advantages of electric and steam drive, tyre rolling, and the economics of electricity in rolling-mills are discussed.

R. Orsettich, *Electricity in American Steelworks* (*Ibid.*, pp. 518-521). The author notes recent progress in plate mills and discusses motors for auxiliary drives. The extensive use of alternating current in American steelworks is noted.

W. E. Swale, *Variable Speed Rolling-Mill Drives* (*Ibid.*, pp. 522-523). The relative advantages of direct and alternating current are

summarised, the conclusion being arrived at that variable speed drives are the most economical, and that the adoption of a constant speed induction motor in conjunction with a speed regulating set, although ingenious and resourceful, is fundamentally unsound.

W. E. Taylor and C. E. Raeburn, *Electric Drive of Rolling-Mills* (Electrician, November 5, 1920, vol. 85, pp. 524-528). The first cost and the energy consumption, involved in the electric driving of rolling-mills are given in detail with tables showing actual steam consumption in lbs. per ton during the rolling down of ingots to blooms. Tables are also given showing time studies of reversing engines and motors, and the economic advantages of using exhaust steam.

W. E. Taylor, *Electrical Driven Tinplate Mills* (*Ibid.*, November 19, 1920, vol. 85, pp. 592-595). A comparison of Welsh and American practice showing the essential differences between the procedure in the two countries, and illustrated by examples taken from the mills of the Canton Sheet Steel Co., U.S.A., and graphs showing the energy consumption.

K. A. Pauly, *The Electric Reversing Mill considered from the Stand-point of Tonnage* (General Electric Review, November 1920, vol. 23, pp. 886-892). The chief advantage of an electrically-driven mill over a steam-driven one is the extremely small loss due to delays of the drive. The article is devoted to a discussion of the influence of the electrical control on the rolling time, and to the effect of limiting the maximum power delivered to the direct-current motor driving the reversing mill.

G. M. Brown, *Power Requirements and Electrical Equipment of Rolling-Mills* (Journal of the West of Scotland Iron and Steel Institute, April 1920, vol. 27, pp. 74-81). A general review of the advantages to be gained by the application of electrical driving to rolling-mills. It is shown that with the electric drive increased speeds and drafts can be used, leading to considerably increased outputs.

W. N. Flanagan, *Modern Steelworks Power Plant* (Paper read before the American Iron and Steel Institute, May 27, 1921).

E. L. Shaner, *Handling Equipment in New Sheet Mill* (Iron Trade Review, November 4, 1920, vol. 67, pp. 1266-1270). The labour-saving equipment of the Newton Steel Co., Newton Falls, Ohio, is described and illustrated. This mill is equipped with a number of mechanical devices, including charging equipment for the annealing and sheet furnaces and an efficient trucking system, which contribute to the economical operation of the plant.

Statistics of Electrically Driven Rolling-Mills.—(Electrician, November 5, 1920, vol. 85, pp. 541-547.) An exhaustive list is given of works in which electrical driven rolling-mills have been installed in the United Kingdom, showing the type of mill, the horse-power and speed, the nature of the energy supplied, and that of the drive. A column is added showing the makers in each instance.

Rolling-Mill Practice.—W. R. Webster, *Application in Rolling of Effects of Carbon, Phosphorus, and Manganese on Mechanical Properties of Steel* (Paper read before the American Institute of Mining and Metallurgical Engineers, September 1921).

G. R. Norton, *Rolling of Variable Section Steel Bars* (Iron Age, January 6, 1921, vol. 107, pp. 42-44). Details are given of the practice at the plant of the Witherow Steel Co., Pittsburgh, for the production of deformed bars, tie rods, automobile axles and shafts, in which the complete conversion of shape is accomplished in one heat. A built-up construction was adopted in which the active faces of the rolls were made of hardened steel segments in which the impressions were cut, the ring formed by the assembled segments being carried over the body of a mandrel which was grooved in its periphery to provide a seat for the inside of the segmental rings, and equipped with devices for locking the segments together. The ends of the mandrels are formed into necks, which serve as journals and to carry the matching and driving gear.

Linard Bar-Rolling Process (Iron and Coal Trades Review, December 3, 1920, vol. 101, p. 759). This new process, which is described, is for rolling small and medium bars. It is a semi-continuous one employing the continuous system for two consecutive housings.

A. Schöpf, *Rolling of Hoop Iron* (Stahl und Eisen, May 13, 1920, vol. 40, pp. 649-651). Theoretical observations and calculations lead to suggested improvements in the practice of hoop-iron rolling. In particular, the final passes should be made in a continuous mill with light rolls and at light pressures.

A. Dyckerhoff, *The Economics of Roll Trains* (Iron Trade Review, January 27, 1921, vol. 68, pp. 279-282). The author discusses the efficiency of mills, which can be increased only by improvement of boilers and driving plant and by reducing the work of rolling, which entails a closer study of roll pass design.

Design of Rolls.—H. R. Ronnebeck, *Foreign Methods of Roll Design* (Paper read before the Cleveland Institution of Engineers, April 4, 1921 : Iron and Coal Trades Review, April 8, 1921, vol. 102, pp. 490-492).

W. H. Melaney, *The Logic of Roll Design* (Blast-Furnace and Steel Plant, January, February, March, 1921, vol. 9, pp. 99-102, 162-163, 210-211). The principles of roll design are discussed and demonstrated.

Removal of Rolling-Mill Scale.—*The Removal of Rolling-Mill Scale* (Zeitschrift für Elektrochemie, 1920, vol. 26, p. 145). In order to meet the scarcity of HCl and H₂SO₄ the use of HF is recommended. It is necessary to make provisions for the removal of acid fumes and the protection of the operators. Scale can be removed by pickling for one hour in 5 to 10 per cent. HF.

FURTHER TREATMENT OF IRON AND STEEL.

Case-Hardening.—W. J. Merten, *New Method for Case-Hardening Steel* (Paper before American Society for Steel Treating; American Drop Forger, October 1920, vol. 6, pp. 481–483). The new process consists in the use of cyanogen gas as a case-hardening medium. The steel or iron articles are heated in a stream of cyanogen gas evolved from a container filled with sodium cyanide, which melts at 600° and boils at 800° C. The steel is independently heated by electric heating elements, out of contact with the fused cyanide, to about 900° C. The speed of the penetration of the nascent gas is four or five times that of carbon monoxide. The nitrogen is returned by a suction fan to the sodium, with which it combines, and by adding charcoal, the supply of cyanide salt can be maintained.

G. R. Brophy and S. B. Leiter, *Cyanide Hardening Due to Nitrogen* (Paper read before the American Society for Steel Treating, September 1920). Steel case-hardened in cyanide contains much nitrogenised material, and nitrogen is believed to exert an appreciable influence on the properties of steel so treated. A 0.04 per cent. carbon steel immersed for four hours in cyanide takes up carbon up to 0.33 on the surface, and when quenched will resist a file. After annealing the cyanided bar is still hard to file, and if the case be ground off the rod is still brittle and remains so after annealing.

H. Fay, *Nitrogen and Case-Hardening* (Chemical and Metallurgical Engineering, February 16, 1921, vol. 24, pp. 289–290). Experiments have been made, the results of which support the conclusion that case-hardening is a nitrogenising as well as a carbonising process. In treating steel by Shimer's cyanamide process, the nitrogen content decreases with rise of temperature, showing that equilibrium is reached at a lower temperature. The maximum nitrogen content was attained at 750° C.

H. M. Crawford, *Case-Hardening with Gas* (Gas Age, 1920, vol. 46, pp. 204–205). The author describes a gas-fired carburising furnace. Gas is used to heat the furnace and to furnish the carburising medium. Almost any penetration can be obtained, depending upon the temperature employed and the amount of gas used in the treating chamber.

T. G. Selleck, *Case-Hardening* (Paper read before the American Society for Steel Treating, September 14–18, 1920). The occurrence of soft spots is discussed.

G. S. McFarland, *A Research in Case Carbonising* (Paper read before the American Society for Steel Treating, September 1920).

A. Matsubara, *Chemical Equilibrium between Iron, Carbon, and Oxygen* (Paper read before the American Institute of Mining and Mechanical Engineers, February 1921). Some of the applications of the theory of carburisation on case-hardening malleable castings, and the reaction between iron, oxygen, and carbon in the blast-furnace were studied.

Waddington, *The Composite Process of Carburisation of Steel during Casting* (Iron and Coal Trades Review, March 4, 1921, vol. 102, p. 311). With the primary object of applying the advantages of limited carburisation to the running surface of steel rails, acid Bessemer steel was poured into a mould having one side lined with amorphous carbon plates, the ingot being rolled into a 95-lb. rail. No difficulties were experienced in rolling, the carburised portion was well marked and kept in its correct position during its passage through the rolls.

Heat-Treating Plant.—*Tunnel Furnace for Continuous Annealing* (Iron and Coal Trades Review, January 14, 1921, vol. 102, p. 49). The furnace described is in operation at the Eston Sheet and Galvanising Works, South Bank, Middlesbrough, for the annealing of steel sheets. It has a total length of 102 feet, and is designed to accommodate six bogies, each 17 feet long. An average output of the furnace is about 750 tons per week on a coal consumption of $1\frac{1}{2}$ cwt. per ton.

F. W. Brooke and G. P. Mills, *Electric versus Combustion Furnaces for Low Temperatures* (Chemical and Metallurgical Engineering, November 24, 1920, vol. 23, pp. 1008–1010). The authors find that electric furnaces have the advantage in temperature control, reliable and permanent source of heat, and maintenance. The cost of power is counterbalanced by economy in space, auxiliaries, and operation.

E. Collins, *Electric Heat Treating of Steel Castings* (Paper read before the American Foundrymen's Association, October 1920). The author enumerates the advantages of electric furnaces, and presents the record of a typical heat to illustrate the uniformity of temperature maintained.

L. W. Wild, *Wild-Barfield Electric Furnace* (Chemical and Metallurgical Engineering, October 6, 1920, vol. 23, pp. 699–700). Illustrated particulars are given of this furnace, which is used for the heat treatment of steel. It is made in three types, namely, radiation, muffle, and salt bath.

T. F. Baily, *Electric Furnaces of the Resistance Type for Heat Treating* (Proceedings of the Steel Treating Research Society, 1920, vol. 2, No. 13, pp. 11–14).

E. F. Collins, *Metallic Resistor Electric Furnaces for Heat-Treating Operations* (*Ibid.*, pp. 23–30).

W. A. Gateward, *Nickel-Chromium and Electric Furnaces* (*Ibid.*, pp. 16–17, 37).

W. A. Gateward, *Electric Furnaces and Methods of Heating* (American Drop Forger, September 1920, vol. 6, pp. 459-462).

A. A. Blue, *Notes on Heat-Treating Equipment* (*Ibid.*, pp. 444-445).

H. O. Swoboda, *Electric Heaters for Heat-Treating Furnaces* (Proceedings of Steel Treating Research Society, 1920, vol. 2, pp. 465-469; American Drop Forger, September, November, 1920, vol. 6, pp. 465-469, 540-543). Electric heaters of the resistor type are described, with an enumeration of the materials used, their physical condition, resistances in ohms per 1000 feet at 68° F., approximate melting points, and names of manufacturers. The second part of the author's paper deals with carbon and graphite resistors, which can be used with excellent results for low temperature furnaces.

R. R. Hillman, *Annealing Steel Castings with Fuel Oil* (Iron Age, January 27, 1921, vol. 107, pp. 247-249). The design and operation of a new oil-fired annealing furnace is described. The furnace is designed to hold a charge of 25 tons. The combustion chamber with three burners is at one end of the furnace, and at the outgoing end is a recuperator through which the incoming blast is passed.

E. F. Collins, *Heat Treating Steel Electrically* (Paper read before the American Foundrymen's Association, October 1920: Iron Trade Review, October 7, 1920, vol. 67, pp. 990-994). The author outlines the advantages of the electric furnace for heat treating. The electric furnace of the resistance type affords a heating atmosphere free from contaminating gases. Automatic control of the temperature is recommended.

E. F. Davis, *The Function of Insulation and Its Application to Heat-Treating Furnaces* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 33-40).

A. M. Redding, *The Application of Pyrometers to the Heat-Treatment of Steel* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 43-49). A review of various types of pyrometers with a discussion of the points to be considered in selecting a pyrometer equipment for heat-treatment installations.

Heat-Treating Plant at Nash Motor Works (Iron Age, April 7, 1921, vol. 107, pp. 895-898). This heat-treating plant, which is situated at Kenosha, Wisconsin, is described. Outstanding features in the equipment are an electric heat-treating furnace, a mixing and conveying system for handling carbonising compound and four double-oven oil-fired carbonising furnaces.

L. M. Thomas, *Plant for Heat Treating Automobile Axles* (American Drop Forger, November 1920, vol. 6, pp. 533-536). A description of the new heat-treatment plant of the Timken-Detroit Axle Company.

Fuels for Heat Treating.—G. H. Trout, *Producer-Gas for Heat Treating* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 51-55). The use of clean producer-gas has

advantages over fuel oil, and can be applied to any ordinary heat-treating furnace by changing the burner.

W. A. Ehlers, *Fuels and their Applications to Metal Treating* (Transactions of the American Society for Heat-Treating, November 1920, vol. 1, pp. 104-111). The advantages, both economic and technical, of powdered coal, liquid fuel, and gaseous fuel for heat-treating furnaces are considered and compared.

A. C. Roessler, *Heat-Treatment using High-Pressure Gas* (American Drop Forger, September 1920, vol. 6, pp. 450-452).

Heat Treatment of Steel.—*Heat Treatment of Steel Castings* (Foundry, November 1, 1920, pp. 859-860; *Giesserei Zeitung*, February 15, 1921, vol. 18, pp. 60-62). The correct temperatures for quenching and annealing of steel castings of various compositions, with a view to improving their tensile properties, are indicated.

J. H. Andrew, *Casting and Treatment of Steel* (Transactions of the North-East Coast Institution of Engineers and Shipbuilders, 1920, vol. 36, pp. 355-380). The mechanical properties of a steel depend primarily upon the degree of fineness of the structure, and it is shown that this can be obtained by three methods: (1) By lowering the point of transformation to such an extent that the decomposition products are unable to coalesce and remain in a fine state of distribution, that is, by the addition of nickel; (2) by the addition of an element such as chromium, which produces a carbide that remains in the finely distributed condition; and (3) by the addition of nickel, chromium, carbon, and an element such as molybdenum, which depresses the transformation temperature still further and enhances the properties dependent on this effect. With regard to impact testing it is necessary, with nickel-chrome steel, that the forgings be water quenched immediately after tempering in order to get good results. With a view to ascertaining the influence of phosphorus, and of heat-treatment on phosphorus steels, impact tests were carried out on a series of nickel steels containing carbon, 0.30 to 0.36; nickel, 3.6 to 3.7; manganese, 0.76; silicon, 0.1; sulphur, 0.01 per cent., while the phosphorus was varied from 0.018 to 0.152. The steel containing 0.018 phosphorus showed very little difference when either quenched in water or allowed to cool slowly in the furnace, while that with 0.152 phosphorus showed values differing by 53 ft.-lbs., according to whether slow cooling or water quenching was employed. A similar specimen which, after slow cooling, was retempered and water quenched from 620° C., gave an impact value of 87, a difference of 86 ft.-lbs. due to heat-treatment.

E. H. Hemingway and G. R. Ensminger, *Surface Changes of Steel Heated in Vacuo* (Paper before American Institute of Mining and Metallurgical Engineers: American Drop Forger, September 1920, vol. 6, pp. 436-441). Experiments were carried out at Watertown Arsenal to determine whether the cause of some peculiar failures of

certain ordnance steels could be traced to the presence of occluded gas and oxides. Low carbon steel containing 0.24 per cent. carbon, and high carbon steel with 1.01 per cent. carbon were heated *in vacuo* for six hours at 1000° C. and allowed to cool, the specimens having been first highly polished. In all of them the polyhedral structure, observed by previous investigators, and known as vacuum relief, was produced. The markings are of three types—a deeply marked polyhedral structure, which represents the final gamma boundaries; a fine clean-cut structure, which can be brought out more clearly by etching, representing the alpha boundaries; and an indefinite, often partly obliterated structure, which represents the boundaries of former gamma crystals that have been absorbed by crystalline growth. The relief figures are produced by the volatilisation and redeposition of iron. The outside layer of the specimen consists of ferrite as a result of the iron having been volatilised and redeposited below the temperature at which solid solution exists. Below 1000° C. iron oxide reacts with the carbides in steel to form carbon monoxide and pure iron.

F. Grotts, *Heat Treating Tractor Castings* (Paper read before the American Foundrymen's Association, October 1920: Iron Trade Review, November 11, 1920, vol. 67, pp. 1346-1348). The author has carried out a number of tests on low, medium, and high carbon, chrome-vanadium, chrome-tungsten, chrome-nickel, and manganese steel castings for tractor parts.

F. Grotts, *Heat Treatment Improves Castings* (Foundry, 1920, vol. 48, pp. 859-860). The strength and elongation of cast steel tractor parts are improved by a quench-and-draw treatment. The dangers from hardening cracks are eliminated by removing castings from water before entirely cool.

C. H. Gale, *Coal affects Sulphur Content in Steel* (Paper read before the American Foundrymen's Association, October 1920: Iron Trade Review, October 14, 1920, vol. 67, pp. 1066-1067). The author gives the results of annealing steel castings with pulverised coal. For a number of years steel castings in the foundry, where the investigations were conducted, had been annealed with natural gas or oil. After the installation of a pulverised coal plant, a marked difference in the physical characteristics of the steel was noticed. The tensile strength was greater with the elongation and reduction in area, and the results of the bend tests less than had been obtained formerly from heats of the same analysis and annealing temperature. Attention was directed to the fuel used, and after investigation it was discovered that the carbon and sulphur content was greatly increased when using coal as fuel, the average analysis for a number of heats being: Carbon, before annealing, 0.262 per cent.; after annealing, 0.287 per cent.; sulphur, before annealing, 0.043 per cent.; after annealing, 0.052 per cent. The coal used was high in sulphur, ranging from 2.45 to 2.80 per cent.

F. Giolitti, *Steel Castings of High Strength and Toughness* (Chemical and Metallurgical Engineering, January 19, 26, 1921, vol. 24, pp. 113-

118, 161-165). The author discusses the effect of correct heat treatment on the physical properties of steel castings, and describes the properties of nickel steel castings which were used for gun parts in place of forgings.

P. Oberhoffer and F. Weisgerber, *The Effect of Annealing on Steel Castings* (Stahl und Eisen, October 28, 1920, vol. 40, pp. 1433-1442). The manner in which the annealing effect is influenced by the thickness of the metal walls of steel castings, as revealed by the tensile tests and microstructure, is considered.

J. H. Hall, *Steel Castings* (Mechanical Engineering, August 1920, vol. 42, pp. 432-434). In considering the conditions under which steel castings can most suitably be used, the dependence of the physical properties upon proper annealing and heat treatment is pointed out.

A. N. Conarroe, *Heat Treatment of Steel Castings* (Foundry, 1920, vol. 48, pp. 596-598). The author discusses the inclusions occurring in steel castings, with special reference to silicate inclusions resulting from the combination of the reaction products with the clay or loam of the refractory linings.

J. H. S. Dickenson, *Notes on the Report of the Steel Research Committee* (Institution of Automobile Engineers, November 10, 1920). A general review of the Report of the Steel Research Committee of the Automobile Engineers on the treatment and properties of special steels suitable for use in automobile construction.

Properties of Heat-Treated Steels (Engineer, November 19, 1920, vol. 130, pp. 510-511). A further review of the above report is published.

G. W. Tall, *Hump Method of Heat Treatment of Steel in Electrical Furnaces* (Proceedings of the Steel Treating Research Society, 1920, vol. 2, No. 13, pp. 18-22).

J. L. McCloud, *Time, Temperature, and Heating Media Functions in Hardening Tractor Worms* (Transactions of the American Society for Steel Treating, November 1920, vol. 1, pp. 116-122).

H. Scott, *Relation of the High Temperature Treatment of High-Speed Steel to Secondary Hardening and Red Hardness* (United States Bureau of Standards, 1920: Scientific Paper, 395). The effect of heat treatment on the density, hardness, microstructure, magnetic properties, and thermal characteristics of high-speed steel are determined. From the investigation it is concluded that a high-speed steel susceptible to secondary hardening is partially austenitic when quenched from a temperature high enough to produce this phenomenon. The microstructure of steels hardened and tempered above 200° is similar to that of carbon steels, although the same nomenclature in certain cases is not permissible. The behaviour of the physical properties of high speed-steel on heat treatment is analogous to that of hypereutectoid carbon steel. The following reasons are given for the use of high heat treatment. Increase of red hardness; increase of initial hardness; and reduction of brittleness. High-speed steel should preferably be tempered for secondary hardness.

J. L. Thorne, *Heat Treatment of High-Speed Steel* (Paper read before the American Society for Steel Treating, September 14-18, 1920).

A. H. D'Arcambal, *The Hardening of High-Speed Steel* (*Ibid.*).

A. F. McFarland, *Note on Double Preheating High-Speed Tools for Hardening* (*Ibid.*).

E. D. Campbell and B. A. Soule, *Reactions in Certain Steels at 930° C.* (Blast-Furnace and Steel Plant, November 1920, vol. 8, pp. 603-604). It is shown that in quenching a steel bar, the difference in the rate of cooling of the two ends of the bar produces changes in chemical constitution which result in differences in thermo-electromotive potential much in excess of anything attributable to experimental error.

W. P. Wood, *The Dimensional Limitation of Successive Heat Treatments of Carbon Steel* (Chemical and Metallurgical Engineering, February 23, 1921, vol. 24, pp. 345-346). The author has studied the shrinkage of carbon steels, of from 0.11 to 1.14 per cent. carbon, due to repeated heat treatment.

K. Iokibe and S. Sakai, *The Change of Rigidity and Logarithmic Decrement of Different Metals by Heating* (Proceedings of the Physical and Mathematical Society of Japan, 1920, vol. 2, p. 93).

L. W. Wild, *Electro-Magnetic Heat Treatment of Carbon Steel* (Electrician, November 5, 1920, vol. 85, pp. 562-563). The application of electro-magnetic methods of heating to carbon steels. Diagrams are given showing the behaviour of eutectoid steel, and examples are given of a method of applying the process to such a steel. The ordinary workshop furnace will not enable the phasing to be carried out with theoretical exactitude, but if certain precautions are taken very satisfactory results can be attained, the method being fairly rapid and easily controlled.

A. H. Miller, *Some Commercial Heat Treatments for Alloy Steels* (Mechanical Engineering, September 1920, vol. 42, pp. 506-508). The object of alloy steel heat treatment is to produce a grain size as small as possible with a degree of hardness suitable for the purpose intended. The three variables which must be controlled for a successful heat treatment are: temperature, time, and rate of cooling, and together with these the influence of mass must not be neglected.

H. B. Smith and F. J. Olcott, *Heat Treatment of Chromium-Nickel Steel Spindles* (Paper read before American Society for Steel Treating: Chemical and Metallurgical Engineering, September 22, 1920, vol. 23, p. 566).

E. Kothny, *Forging Tests on Nickel-Chrome Steel* (Stahl und Eisen, February 17, 1921, vol. 41, pp. 213-223). A long account of the manufacture, treatment, and testing of nickel-chrome aero-crankshafts.

S. A. Hand, *Manganese Steel and Methods of Machining It* (American Machinist, European and Colonial Edition, March 5, 1921, vol. 54, pp. 43-45). The heat treatment and the methods of grinding manganese steel are briefly discussed.

R. R. Abbott, *Heat Treatment of Automobile Steels* (Paper before American Iron and Steel Institute, October 22, 1920). Discussion of practice in the heat treatment of automobile steels.

H. J. French, *Some Applications of Alloy Steels in the Automotive Industry* (Mechanical Engineering, September 1920, vol. 42, pp. 501-505). Various types of nickel-chromium steels are used in the automobile industry, and particular reference is made to the properties and hardness of steel containing 1 per cent. nickel and 1 per cent. chromium, also 3 per cent. nickel and 3 per cent. chromium, when subjected to varying heat treatments. Curves showing the tensile properties and hardness of stainless steel under different conditions of oil-quenching and tempering are presented. Results of cutting tests with cast high-speed steel milling cutters are given.

R. M. Taylor, *Steel for Machine Parts* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 67-72). The system of the American Society of Automobile Engineers for the classification of steels and for specifying the requirements and necessary heat treatment is explained.

B. F. Tillson, *Breakage and Heat Treatment of Rock-Drill Steel* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921). The kinds of drill steel in use, the forces acting on drill steel, including wave transmission, and the stresses found in drill steel, are discussed.

J. H. Herron and A. L. Wurster, *Composition and Hardening of Die Blocks* (Forging and Heat Treating, January 1921, vol. 7, pp. 34-36). Practical advice is given as to the most suitable material and heat treatment for drop-hammer dies.

L. Guillet, *Heat Treatment of Metallurgical Products* (Revue Générale des Sciences, July, October, 1920, vol. 31, pp. 523-547, 564-581, 614-620). Deals generally with the effect of quenching, tempering, and annealing on the physical and mechanical properties of steel.

J. F. Springer, *Heat Treating Metals with Gas* (Gas Age, 1920, vol. 46, pp. 198-202). The author deals with the application of gas for forging, case-hardening, tempering, and annealing of steel.

J. Cournot, *Annealing of Electrolytic Iron* (Comptes Rendus, 1920, vol. 171, pp. 170-171; Revue de Métallurgie, Mémoires, August 1920, vol. 17, pp. 568-570). Hydrogen contained as hydride, which increases the hardness of electrolytic iron, can be removed by annealing at fairly high temperature. To determine the conditions required for its removal, the author heated small test-pieces both in a fused salt bath and in a gas-fired furnace at different temperatures. The test-pieces were subsequently polished and etched. The grain size of the crystal structure increased with the annealing temperature. From 650° to 750° the characteristic hydride structure partially disappeared, and for 850° and higher temperatures it wholly disappeared. The results show that two hours at 950° or one hour at 1050° is necessary for complete annealing; four hours at 850° does not suffice. The

hydride structure wholly disappeared after one hour at 850° , but the hardness had not then reached its minimum.

G. Tammann, *Temper Colours of Metals and the Colouring of Steel* (Nachrichten der Kgl. Gesellschaft der Wissenschaften zu Göttingen; Stahl und Eisen, October 14, 1920, vol. 40, pp. 1378-1379). A discussion of the theory of temper colours. Temper colours are only produced when connected layers are formed on the surface of the heated metal. If the product of the reaction collects in the form of sub-microscopic crystals, no colours are produced; neither do they occur unless the thickness of the connected layer of the product of reaction is over 50 atoms deep.

V. E. Hillman, *The Efficiency of Various Quenching Mediums and their Application* (Paper read before the American Society for Steel Treating, September 14-18, 1920).

P. Chevenard, *Apparatus for the Thermal Analysis of Steel* (Revue de Métallurgie, Mémoires, October 1920, vol. 17, pp. 687-695). A simplified apparatus for recording the transformation points in steel specimens is illustrated and described.

A. Sauveur, *Temperature Conversion Tables* (Chemical and Metallurgical Engineering, December 1, 1920, vol. 23, p. 1075). The tables range from -459.4° F. to 543.2° F., and are arranged in three columns, the centre one referring to the temperature either in degrees C. or F. which it is desired to convert, the equivalent temperature being found in the other columns.

Welding and Cutting.—H. Brearley, *The Welding of Steel in Relation to the Occurrence of Pipe, Blowholes, and Segregates in Ingots* (Proceedings of the Cleveland Institution of Engineers, December 13, 1920, pp. 47-87. See also this Journal, pp. 27-62).

O. H. Eschholtz, *Metal Deposition in Arc Welding* (Electrical World, June 26, July 17, 1920, vols. 75, 76, pp. 1473-1475, 118-121). The transfer of metal from a wire electrode to the weld may be accomplished partly by vaporisation and condensation of electrode material, by expulsion of vaporised and liquefied metal by the expansion of gases confined or generated in the electrode ends, and by transport of liquefied metal by molecular attraction, gravity, or surface tension. It is concluded that under good welding conditions at least 85 per cent. of the deposited metal is transmitted in liquid form through the action of molecular forces. The proportion of electrode vaporised probably does not exceed 5 per cent.

O. H. Eschholz, *Metallic Electrode Arc-Welding Process* (Mechanical Engineering, October 1920, vol. 42, pp. 572-574). The phenomena connected with the transition of metal in fusion welding are described, and results of tensile tests on arc-deposited metal are given.

O. H. Eschholz, *Overhead Arc Welding* (Electric World, November 13, 1920, pp. 966-969). Describes the manipulations

necessary for carrying out overhead welding with the metallic arc process.

H. S. Rawdon, *The Electric Arc Welding of Steel: The Properties of the Arc-Fused Metal* (Mechanical Engineering, October 1920, vol. 42, pp. 567-571). The investigation is concerned with the properties of arc-fused metal, in order to study the composition changes which accompany fusion, and the mechanical properties and structure after fusion. The most noticeable change in composition was the increase in the nitrogen content of the steel. Fracture in all cases revealed interior flaws and defects. The tensile properties are similar to those of steel castings of a rather inferior grade.

H. S. Rawdon, E. C. Groesbeck, and L. Jordan, *Physical Properties of Arc-Fused Steel* (Chemical and Metallurgical Engineering, October 6, 1920, vol. 68, pp. 677-684). The investigation was concerned primarily with the properties of the arc-fused metal, and regular welds were not made. Instead the metal was deposited in a block large enough to permit a tension specimen (0.505 in diameter, 2 inches gauge length) to be machined out of it. Although the opinion is held by some welders that the properties of the metal of an arc weld are affected materially by the adjacent metal by reason of the interpenetration of the two, it was decided that the change of properties of the added metal induced by the fusion alone was of fundamental importance and should form the basis of any study of arc welding. Two types of electrodes were used as material to be fused. These differed considerably in composition, and were chosen as representative of a "pure" iron and a low carbon steel. The arc-fused metal gave mechanical properties like an inferior porous casting and notably deficient in ductility. The loss of carbon and silicon is very marked in each case where these elements exist in considerable amounts. A similar tendency may be noted for manganese. The most notable change in composition is the increase of the nitrogen content of the metal.

H. S. Rawdon, E. C. Groesbeck, and L. Jordan, *Metallography of Arc-Fused Steel* (Chemical and Metallurgical Engineering, October 20, 1920, vol. 23, pp. 777-784). The present study forms a part of the previous investigation by the same authors. Microscopic examination of bent pieces of arc-fused metal shows that the metallic grains are inherently ductile. The view that the characteristic features observed in the structure of the arc-fused iron are due to the increased nitrogen is supported by different lines of evidence.

A. M. Candy, *Arc-Welding Problems* (Paper read before the American Foundrymen's Association: Iron Trade Review, March 24, 1921, vol. 68, pp. 829-835). The author has also studied the physical characteristics of arc-deposited metal, and discusses the factors upon which good welding is dependent, with special reference to the welding of castings.

A. M. Candy, *Arc Welding and Cutting Practice for the Foundry*

(Paper read before the American Foundrymen's Association, October 1920). The problems encountered in welding various types of castings are outlined. The use of several types of electrodes is described and the electrical features of arc welding and cutting equipment dealt with.

F. P. Vaughan, *Practical Applications of Electric Welding* (Journal of the Engineering Institute of Canada, 1920, vol. 3, pp. 556-564).

F. H. Williams, *Electric Welding* (Journal of the Engineering Institute of Canada, 1920, vol. 3, pp. 514-521). The author traces the history of electric welding methods and gives a brief account of research work on the subject.

A. K. Dawson, *The Electric Welding of a Corroded Boiler Shell* (Transactions of the Institution of Mining Engineers, November 1920, vol. 60, pp. 8-12).

Electrically Welded Tyre Rims (Iron and Coal Trades Review, November 5, 1920, vol. 101, p. 622). Particulars are given of the results of a number of tensile tests made upon welded and unwelded steel tyres for motor lorries.

H. B. Payne, *Welding Steel Structural Work* (Electrical World, June 19, 1920, vol. 75, pp. 1421-1422). Particulars are given of the costs, the conditions of testing, and the results of tests of electrically welded steel construction work.

Electric Welding (Automobile Engineer, March 1921, vol. 11, pp. 105-109). Notes are given on the various methods of electric welding and machines employed for the purpose. The illustrations show instances of repair work on complicated automobile parts.

D. F. Miner, *Developments in Electro-Percussive Welding* (Iron Age, October 21, 1920, vol. 106, pp. 1040-1041). The apparatus employed consists of a device for producing a percussive engagement of the parts to be welded simultaneously with the electrical discharge.

S. W. Miller, *Testing Gas and Electric Welds* (Paper read before the American Welding Society, September 1920 : Iron Trade Review, November 18, 1920, vol. 67, pp. 1406-1409 ; Blast-Furnace and Steel Plant, December 1920, vol. 8, pp. 678-683). The author outlines the methods available for testing oxyacetylene and arc welds. In determining the strength of oxyacetylene welds, the bend test is one of the most important.

F. M. Farmer, *Standardised Tests of Welds* (Paper read before the Institution of Mechanical Engineers : Engineering, February 25, 1921, vol. 3, pp. 239-242). Three standards of tests for welds are suggested—shop standard, commercial standard, and research standard. For the shop standard a bending test is sufficient, as it yields more information concerning the important properties of the material than any other single static test. For the commercial standard a bending test, tensile test, and fatigue test are suggested. The research standard would include chemical analysis and metallographic examination, besides all the recognised mechanical tests.

C. Fremont, *Blue Brittleness of Steel Welds* (Comptes Rendus,

1921, vol. 172, pp. 368-370). In electric welding, if sufficient pressure is exerted to squeeze out all the metal oxidised at the beginning of the operation, a joint is obtained free from oxidised metal, which may be satisfactory, but if deformation takes place within a region where the temperature is between 200° and 450° C., blue brittleness will result.

A. S. Kinsey, *Cutting Cast Iron with Oxyacetylene Torch* (Paper read before the American Foundrymen's Association, October 1920). The principle of cutting metals by the oxyacetylene process is outlined, and the methods of cutting cast iron, the best type of torch, and the gas pressures to be maintained is discussed.

Manufacture of Tubes.—H. C. Ebright, *Manufacture of Steel and Iron Tubes* (Blast-Furnace and Steel Plant, November 1920, vol. 8, pp. 609-612). The method of the Youngstown Sheet and Tube Company for manufacturing pipes and the processes used in forming and welding steel tubes are described.

K. Gruber, *Mannesmann Oblique-Rolled Seamless Tubes* (Iron Age, April 7, 14, 21, 28, 1921, vol. 107, pp. 903-905, 977-980, 1011, 1049-1052, 1114-1118). A translation of the article by Gruber which originally appeared in *Stahl und Eisen*, Sept. 4-Oct. 16, 1919, vol. 39.

Manufacture of Springs.—T. D. Lynch, *A Process for the Manufacture of Helical Springs for Heavy Duty* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 62-67). Conditions are laid down for the manufacture and heat treatment of helical springs made of crucible or electric steel of the following composition :

	Per Cent.
Carbon	0.50 to 0.60
Manganese	0.60 „ 0.80
Phosphorus	Not over 0.04
Sulphur	„ „ 0.04
Silicon	1.90 to 2.20

D. F. Kennedy, *Modern Automobile Spring Manufacturing* (Iron Age, January 6, 1921, vol. 107, pp. 19-22). The manufacture of springs for automobiles as carried out at the plant of the Detroit Steel Products Co. is described.

Manufacture of Chains.—C. G. Lutts, *Chain Cable and Some of its Physical Properties* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II. pp. 80-101). A description of the manufacture and tests of power-forged wrought iron chain cable at the Boston Navy Yard.

P. M. Tyler, *The Chain Industry in Great Britain* (Iron Age, January 20, 1921, vol. 107, pp. 183-186). A discussion of the conditions and methods of manufacturing chains, with particulars regarding labour, wages, and other costs.

Wire and Wire Rope Manufacture.—L. D. Granger, *Modern Process of Drawing Wire* (Blast-Furnace and Steel Plant, December 1920, vol. 8, pp. 661–663). The practice followed in wire drawing is described, the processes dealt with being those for the production of soft wire, hard wire, and net wire.

G. W. Westgarth, *Wire Ropes* (Paper read before the South African Institution of Engineers: Iron and Coal Trades Review, March 25, 1921, vol. 102, pp. 436–437). The author traces the most important developments in the manufacture of wire rope, and compares some of their fundamental principles to indicate some of the weaknesses, or defects, and describes a new type of rope.

Making a Colliery Winding Rope (Iron and Coal Trades Review, October 1, 1920, vol. 101, p. 440). The various processes involved in the manufacture of colliery haulage and winding ropes as carried out at the works of the Whitecross Company, Ltd., Warrington, are described.

Manufacture and Properties of Stainless Steel.—E. Haynes, *Stainless Steel* (Paper read before the American Iron and Steel Institute, May 27, 1921). A short account of the manufacture, properties, and uses of stainless steel.

J. H. G. Monypenny, *Stainless Steel* (Journal of the Society of Chemical Industry, November 30, 1920, vol. 39, pp. 390–391-R). Stainless steel contains essentially 11 to 14 per cent. of chromium and, for most purposes, not more than 0.45 per cent. of carbon. Up to 1 per cent. of nickel is also often contained, but this element has no beneficial effect on the non-corrodible properties, while its presence may cause trouble in the heat treatment of the steel. The steel possesses air-hardening properties, and a sample of about 1 inch diameter, cooled freely in air from 900° C., will have a Brinell hardness of 500. After oil- or air-hardening from 900°, followed by a slight tempering at 200° to 400° C., its mechanical properties are comparable with those of the "100-ton" air-hardening nickel-chrome steel. It is especially suitable for aeroplane valves on account of its superior tensile strength at high temperatures.

W. H. Marble, *Stainless Steel: Its Treatment, Properties, and Applications* (Paper read before the American Society for Steel Treating, September 14–18, 1920).

Hardware.—E. L. Shaner, *Making Pressed Metal Parts* (Iron Trade Review, March 3, 1921, vol. 68, pp. 617–620). The author discusses the principle of shaping sheet and bar metal between dies in power presses, and traces the development of this industry in the United States.

Hardware in the Making (Hardware Trade Journal, November 26, December 17, 24, 1920; January 7, 14, 21, 28; March 25, June 3, 1921, vol. 102, pp. 662–663, 916–917, 1004–1005; vol. 103, pp. 11–12, 87–88,

162-163, 249-250, 645-647, 996-998, &c.). The production of locks, scissors, spoons and forks, and cutlery, the enamelling of sheet iron and steel, the manufacture of razors, and the processes involved in the production of hollow-ware are dealt with.

Pickling.—*Pickelette* (Iron and Coal Trades Review, December 3, 1920, vol. 101, p. 763). This new substance is described as a complicated organic mixture, and the introduction of a minute proportion of it into a pickling bath is said to greatly retard the attack of the acid on the iron and steel surfaces after the scale is removed, while not affecting the action of the acid in removing the scale.

V. E. Hillman, *Acid Brittleness* (Edgar Allen News: Foundry Trade Journal, November 1920, vol. 22, p. 854). When steel is subjected to a pickling operation, a phenomenon known as "acid brittleness" occurs. During the cleaning process the steel has a tendency to absorb the hydrogen gas that is liberated from the bath. The steel is rendered extremely brittle by the assimilated gas. Heating the acid brittle steel to 400° F. drives off the absorbed hydrogen gas and restores the steel to its normal condition.

Enamelling.—H. Beyer, *The Enamelling of Cast Iron* (Giesserei Zeitung, February 15, March 1, 15, 1921, vol. 18, pp. 53-56, 71-74, 91-92). For the successful enamelling of cast iron, the quality and composition of the iron is a very important consideration, as the casting must be able to stand annealing several times without cracking. According to the thickness of the metal, the silicon should be from 2 to 2.6 per cent. Too low a percentage of silicon may lead to the formation of iron carbide making the metal hard and liable to crack. If the silicon exceeds a maximum of 2.6 per cent. it causes too great a separation of graphite, which prevents the adhesion of the enamel. Manganese should not exceed 0.6 per cent., as it makes the metal too brittle. Phosphorus should not be lower than 1 per cent. Sulphur must be kept as low as possible. If it exceeds 0.14 per cent. the manganese requires to be increased somewhat in order that the excess sulphur may be taken up in the slag in the form of sulphide of manganese. Porous castings can never be satisfactorily enamelled, for the reason that, as the metal cools after annealing, air is drawn into the pores and draws with it the still semi-fluid enamel coating, causing a fault in the surface. Sandy spots or veins on the surface of the casting are also a trouble, as the thin enamel coating will not adhere to them, but contracts, leaving them bare. The process of enamelling and the nature of the enamel and its preparation are described.

J. B. Shaw, *Enamels for Sheet Iron and Steel* (United States Bureau of Standards, 1920: Technologic Paper 165). This report includes a description of the properties and preparation of steel for enamelling, raw materials for enamels, preparation of enamels, enamelling process,

calculation of enamel formulas, physical properties, and resistance of enamels to chemical action.

C. G. Armstrong, *Porcelain Enamelling Furnaces* (Chemical and Metallurgical Engineering, March 16, 1921, vol. 24, pp. 486-488). The points of weakness in the old types of enamelling furnaces are outlined, and the latest developments in furnace construction are discussed.

Coating of Metals.—J. R. Wemlinger, *Installing a Small Galvanising Plant* (Iron Age, January 13, 1921, vol. 107, pp. 123-125). The author discusses the equipment and materials necessary for the galvanising of sheets. Details of the process are also given.

W. Kasperowicz, *Zinc Coatings Applied by Means of Hot Compressed Air* (Zeitschrift für Elektrochemie, 1920, vol. 26, pp. 121-122). Zinc powder is introduced into a jet of hot air. Owing to the cooling effect of the expanding compressed air, the molten particles of zinc are impinged on the iron surface without appreciable oxidation.

C. F. Poppleton, *Sixty Years Progress in Galvanising* (Iron Trade Review, April 28, 1921, vol. 68, pp. 1170-1174). The author traces the developments that have taken place in the galvanising of iron and steel.

C. F. Poppleton, *Tinning Methods and Tin House Equipment* (Iron Age, January 20, 1921, vol. 107, pp. 187-191). The arrangement of a modern tinline plant and machinery for coating and cleaning is described, together with particulars of the new Thomas automatic tinning machine in operation at the Melingriffith Works, South Wales.

M. Schlötter, *Nickel Plating and Cobalt Plating* (Stahl und Eisen, March 3, 1921, vol. 41, pp. 293-297). The conditions for the satisfactory plating of metals with nickel and cobalt are discussed.

A. V. Farr, *Calorising as a Protection for Metals* (Iron Age, January 27, 1921, vol. 107, pp. 251-253). The author deals with recent developments as applied to copper and brass as well as steel. The depth of penetration and the various applications of the process are discussed.

Protective Metallic Coatings for the Rustproofing of Iron and Steel (United States Bureau of Standards, 1919, Circular 80).

S. Cornell, *Finish of Metallic Materials* (Chemical and Metallurgical Engineering, February 2, 1921, vol. 24, pp. 209-212). Brief notes are given on the cleaning, polishing, lacquering, and coating of metal surfaces.

S. Cornell, *Bluing and Browning Steel Articles* (Chemical and Metallurgical Engineering, February 16, 1921, vol. 24, pp. 301-303). A brief description of several commercial methods of producing an oxidised finish on polished steel articles, including analyses of several browning solutions in use.

PHYSICAL AND CHEMICAL PROPERTIES.

Properties of Cast Iron.—R. Ruer and J. Biren, *Solubility of Graphite in Molten Iron* (Zeitschrift für anorganische Chemie, 1920, vol. 113, pp. 98–112). In molten Swedish iron the solubility of graphite increases as the temperature rises from 1152° C. to 2700° C. The solubility curve follows a straight line from 1152° C. to 1700° C. It then bends away from the concentration axis, the deviation becoming sharper as the temperature increases. The eutectic point for graphite at 1152° is 4.25 per cent. carbon, and for cementite at 1145° it is 4.30 per cent. carbon.

K. Iokibe, *The Crystalline Nature of Graphite and Temper-Carbon obtained from Cast Iron* (Tôhoku Imperial University : Science Reports, August 1920, vol. 9, pp. 275–279). The conclusion is drawn that the so-called graphite carbon and the temper carbon as found in cast iron are both the same substance as natural graphite. Since the conditions of the decomposition of cementite are the same both for steel and cast iron, the temper carbon from carbon steels will also be graphite and not an amorphous carbon.

E. L. Rhead, *Cast Iron: The Strength and Properties of Castings* (Technology : Journal of the Manchester College of Technology, 1920, vol. 10, pp. 57–85). The influence of elements on the strength of castings is considered, also their effect in producing segregation and porosity.

F. G. Cook, *Mechanical Tests for Cast Iron* (Paper read before the Institution of British Foundrymen, November 18, 1920 : Foundry Trade Journal, February 10, 17, 1921, vol. 23, pp. 132–134, 149–150). The author discusses the influence of elements on cast iron, and enumerates the more important tests which are of use as a guide to foundrymen.

Schmauser, *Effect of Sulphur on Walls of Castings of Different Thickness* (Giesserei Zeitung, October, November, December, 1920, vol. 17, pp. 309–313, 335–338, 353–356, 367–373, 383–386, 402–404).

A. Geissel, *Cast Iron for the Chemical Industry* (Giesserei Zeitung, 1919, vol. 16, pp. 257–260, 292–298). Acid-resisting cast-iron ware requires to be of homogeneous, very fine-grained metal. Cast iron for vessels to contain alkalies should have a low silicon and phosphorus content, as potash and soda liquors dissolve silicon, and hot potash liquor takes up phosphorus. Manganese resists the attack of alkali liquors, but colours them brown.

C. H. Strand, *Cast Iron for Locomotive Cylinder Parts* (United States Bureau of Standards, 1920, Technologic Paper 172). From a number of tests carried out by the Bureau it is concluded that air-furnace iron, or so-called "gun iron," is more uniform in character and on the average has somewhat better mechanical properties than cupola iron. The latter, however, often equals or even excels in mechanical properties the specimens of air-furnace iron used in the investigation. The sulphur content of the air-furnace iron examined seldom exceeded 0.06 per cent., while the cupola iron varied in sulphur content from 0.10 to 0.17 per cent. It was impossible, except in a general way, to find any correlation between the quality of iron as developed in the laboratory tests and the mileage obtained in service. This is explained by the fact that many other factors enter into consideration, namely, design, lubrication, and methods of handling the locomotive.

E. Leuenberger, *Influence of Manganese on the Tensile Properties of Malleable Cast Iron* (Stahl und Eisen, March 3, 1921, vol. 41, pp. 285-287). It has generally been held that the permissible percentage of manganese in malleable castings should not exceed about 0.4 per cent. In the absence of any data in support of this assumption, experiments have been made to determine the influence of manganese. The following conclusions were arrived at: The tensile strength increases with an increase of manganese; up to about 1 per cent. of manganese the elongation is not affected, but with over 1 per cent. the elongation is reduced; the tensile strength diminishes and the elongation increases if the annealing period is prolonged beyond 95 hours; if the annealing period is prolonged to 260 hours, the manganese can be increased to 1.5 per cent. without lowering the elongation.

W. R. Bean, H. W. Highriter, and E. S. Davenport, *Fractures and Microstructures of American Malleable Cast Iron* (Paper read before the American Foundrymen's Association, October 1920). The authors explain the causes of various fractures of malleable cast iron that occur in regular operating routine.

A. T. Lowzow, *Influence of Silicon upon the Properties of Ferro-Silicon* (Chemical and Metallurgical Engineering, March 16, 1921, vol. 24, pp. 481-484). A series of samples containing from 49.1 to 93.41 per cent. of silicon were examined and their microstructure is described.

Testing Appliances.—D. J. McAdam, Jun., *A High-Speed Alternating Torsion Testing Machine* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II., pp. 366-370). In the apparatus described and illustrated the inertia of a moving mass is used as a means of applying and measuring torsional stress.

C. H. Marshall, *Improved Elastic Limit Recorder* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II., pp. 361-365). A new method for making rapid elastic determinations

on a commercial scale has been introduced in the physical testing laboratory of the Westinghouse Electric and Manufacturing Company. A device is employed by which the elongation and load are plotted simultaneously in the form of a curve, and tests for finding the elastic limit require very little more time than straight tension tests.

P. Ludwik, *A New Method for Determining the Ductility of Metals and Alloys* (Stahl und Eisen, November 18, 1920, vol. 40, pp. 1547-1551). For roughly determining the toughness and ductility of a metal, without first preparing test-bars, a hardened steel cone, pointed to an angle of 90° , is pressed into the surface of the piece near the edge until a crack occurs. If a is the amount of projection of the bulge beyond the original edge, and k the original distance of the point of the cone from the edge, the ratio $a : k$ gives approximately the measure of ductility. It can be more approximately calculated from dimensional measurements of the impression.

T. Y. Olsen, *Ductility Testing Machines* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II., pp. 398-403). The machine tests the ductility of metal sheets by cupping with a handwheel and screw. The new feature consists in providing means for measuring the power necessary to produce a certain depth of cupping as well as the amount of cupping causing fracture.

H. S. Primrose and J. S. G. Primrose, *New Types of Machines for Hardness Testing* (Proceedings of the Institution of Mechanical Engineers, 1920, pp. 933-954). Two new types of machines for testing hardness are described.

The Rockwell Hardness Tester (Foundry Trade Journal, October 1920, vol. 22, p. 778). This hardness testing apparatus is claimed to be able to test various metals which cannot be tested by Brinell and scleroscope machines.

J. L. Jones and C. H. Marshall, *New Method for Calibrating Brinell Hardness Testing Machines* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II., pp. 392-395). The authors describe a balance which consists of a single beam and support to be used in checking Brinell testing apparatus.

R. Guillery, *A Study of the Ball-Hardness Test* (Mémoires de la Société des Ingénieurs Civils de France, 1920, vol. 73, pp. 591-606; Revue de Métallurgie, Mémoires, February 1921, vol. 18, pp. 101-110). A modification of the Brinell ball press has been devised by which the influence of the time of maintaining the pressure is eliminated. The ball is carried on the end of a small ram actuated by means of hydraulic pressure, the medium used being glycerine, on which pressure is exerted or released by means of a hand-lever.

W. J. Francke, *Apparatus for Delicate Flexure Tests and Results of such Tests* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II., pp. 372-386). A new apparatus for measuring deflection and bending is illustrated and described. In tests made with it, six points representing physical changes in the material are

developed, namely, fatigue, fatigue range, yield point, yield range, plastic limit, and rupture. Definitions of these several terms are given.

Tests and Properties of Materials.—Retzow, *Hardness Investigation of Material Subject to Compression* (Stahl und Eisen, March 18, 1920, vol. 40, pp. 399–401). In all steel material subject to cold-working by compression, it is necessary, in determining the hardness, to test not only the external surface but the inner layers as well.

J. Innes, *Measurement of High Degrees of Hardness* (Proceedings of the Institution of Mechanical Engineers, 1920, pp. 915–932). The definition and measurement of hardness are discussed, and it is shown that hardness depends on the elastic properties of a material.

B. P. Haigh, *Prism Hardness: A New Test for Hardness* (*Ibid.*, pp. 891–913). A new method of testing hardness in materials is described, in which a pair of test-pieces of the same material are used, by making them indent one another. The pieces take the form of square prisms placed crosswise with their edges in contact, and they are pressed together by a constant load. Consistent hardness values may be obtained by dividing the applied load by the square of any characteristic linear dimension of the indentations produced, width or depth, whichever may be preferred.

H. S. Rawdon and E. Jimeno-Gil, *Relation between the Brinell Hardness and the Grain Size of Annealed Carbon Steels* (United States Bureau of Standards, Scientific Paper No. 397). The Brinell hardness was determined for five steels varying in carbon content from a very low value to somewhat above 1 per cent. Upon heating for six-hour periods no very appreciable increase in the grain size occurred until the Ac₃ transformation in the steel had taken place. The change in grain size often appeared to take place with a narrow range of temperature. Although it was impossible to obtain an accurate numerical grain size determination for many of the specimens, the micrographic examination indicated that there is no simple and direct relation between grain size and Brinell hardness number for carbon steels. A very pronounced increase in grain size is usually accompanied by a decrease in hardness. On the whole, however, grain size appears to be a factor of minor importance in determining the Brinell hardness of carbon steels of the types investigated.

S. Idei, *The Distribution of Hardness in Quenched Carbon Steels* (Proceedings of the Physical and Mathematical Society of Japan, 1920, vol. 2, p. 93).

T. E. Stanton and R. G. C. Batson, *Characteristics of Notched-Bar Impact Tests* (Paper before Institution of Civil Engineers, November 30, 1920). While the value of the impact test in discriminating between correctly and incorrectly heat-treated material has long been recognised, the chief obstacles to its standardisation have been (1) the difficulty of obtaining a more definite interpretation of the test so as

to determine the relation of the results to the impact strength of the materials in practical use; and (2) the variability of the results of individual tests. A complete series of tests was made at the National Physical Laboratory on a low-carbon steel, a high-carbon steel, and Yorkshire iron, with the object of investigating the effect on the work of fracture and consistency of the results obtained of a variation in the angle of the notch in 10 by 10 millimetre specimens; also the sensitivity of the various types of V-notch in revealing faulty heat treatment. The results showed that the work of fracture has its lowest value when the angle at the bottom of the notch is as nearly zero as it can be made. The variations in the results of individual tests are not inherent in the method of test but are due to inhomogeneity in the material. This confirms G. Charpy's conclusion (*Journal of the Iron and Steel Institute*, 1917, No. II.). The form of specimen 10 by 10 millimetres, developed by the Aeronautical Inspection Department, which used a 45° notch with a radius of 0.25 millimetre at the bottom, is equally as effective as the forms used by Charpy and Frémont. Five geometrically similar test-pieces with different cross-sectional dimensions were also tested, the results showing that it was impossible to predict which was the safest material to use in a structure subject to vibration and shock except by experiments on a full scale. The value of the test lies, not in discriminating between the impact resistances of different materials, but in showing whether the impact strength of any given material is at its highest. The effect of the striking velocity was also studied. It was found in general that the speed effect depended on the nature of the material tested, and that increased speed did not necessarily imply a reduction of the energy for fracture.

R. H. Greaves and H. Moore, *Notes on the Single Blow Impact Test on Notched Bars* (Paper read before the Institution of Civil Engineers, November 30, 1920). The authors describe the results of experimental work on notched-bar test-pieces from oil-hardened and tempered carbon, nickel and nickel-chromium steel forgings. They conclude that (1) the 0.25 millimetre radius V-notch test-piece specified by the British Engineering Standards Association appears to be the most satisfactory as regards discrimination between tough and brittle material, uniformity of results, and ease of machining. (2) Variations in the radius of the notch below 0.25 millimetre result in differences in impact figure, which do not on an average exceed 2 ft.-lbs. in the case of the steels used. (3) Other conditions remaining the same, an increase in energy absorbed (from E_1 to E_2), and for steels of the same type over a wide range of impact figure, $E_2 = E_1 + \text{a constant}$. (4) The regularity of the results for certain types of steel is sufficient to enable the impact figure given, by one of the forms of notch and machine used, to be deduced approximately from that given by another form of notch and machine.

Sir R. A. Hadfield and S. A. Main, *Shock Tests and Their Standardisation; Including the Effect of High Velocities on Impact*

up to 2870 Feet per Minute (Paper before the Institution of Civil Engineers, December 14, 1920). Examples are given of the remarkable effect on the impact value which may be produced in steel by different heat treatments. The effect of velocity of impact is shown by a set of tests on an overheated mild steel. A notched Frémont specimen when tested slowly bends through 131° without fracture with an expenditure of 38.5 kgm. (280 ft.-lbs.). An exactly similar specimen tested in the Frémont machine breaks with a crystalline fracture; the bending angle being less than 1° and the impact resistance only 1 kgm. (7 ft.-lbs.). In the present state of knowledge, complete standardisation of the shock test does not seem possible.

R. M. Jones and R. H. Greaves, *Effect of Overstrain on the Impact Figure of Steel* (Paper before the Institution of Civil Engineers, November 30, 1920). Notched-bar impact tests were made under standard conditions in the 120 ft.-lb. Izod machine on heat-treated carbon and nickel-chrome steels, which had undergone varying degrees of overstrain. In each case the impact figure was progressively reduced by increasing amounts of overstrain, and was still further lowered by low temperature annealing. Cold-work of any kind produces the same effect on the impact figure.

G. Berndt, *The Importance of the Impact Test* (Technische Rundschau, 1920, vol. 26, pp. 57-59; Zeitschrift für Metallkunde, June 15, 1920, vol. 12, pp. 221-222). Forty specimens of open-hearth steel were tested with the Charpy impact pendulum machine, and the values obtained for the mechanical properties were arranged according to the amount of the work of rupture. Small variations in the treatment of the specimens caused the work of rupture to vary by as much as 150 per cent., but it was observed that the other values were subject to a very much smaller degree of variation. The results showed that as the notch-toughness increased, the limit of elasticity, yield point, and hardness at first rose sharply to a maximum (at 1.3 kgm. notch-toughness), then fell suddenly to a minimum (at 1.65 kgm.), from which point onwards all those properties remained fairly constant. The elongation was affected exactly in the reverse way, and remained constant after reaching a maximum at 1.65 kgm. In testing shell steel during the war, it was always found that as the notch-toughness increased the fragments on bursting were larger.

L. Guillet and Legrand, *Comparative Impact Tests* (Revue de Métallurgie, Mémoires, April 1921, vol. 18, pp. 221-224, 225-228). Two reports are presented on comparative impact tests made with the Charpy test-bar, a test-bar devised by Mesnager, and with the new test-bar of the Commission of Standardisation. The bars are all of the same dimensions, the form of notch being different in each case. The values obtained for each bar appear to differ consistently from those for the other types of bars.

L. Guillet, *Duration Impact Tests* (Revue de Métallurgie, Mémoires, February 1921, vol. 18, pp. 96-100). The author emphasises the fact

that it is not a sufficient indication of the quality of a metal to show a high resistance to impact, but it must also show a high elastic limit. A low resistance to impact accompanied by a high elastic limit is greatly to be preferred to the reverse condition.

A. Cornu-Thenard, *An Experimental Study of Impact Tests on Notched Bars* (Revue de Métallurgie, Mémoires, September, October, 1920, vol. 17, pp. 584-614, 648-667). The articles form the second part of an exhaustive research on the influence of speed of impact, the influence of the shape of the notch, and the law of similarity, in tests of steel in various conditions of heat treatment.

E. G. Coker, *Tension Tests of Materials* (Engineering, January 7, 1921, vol. 3, pp. 1-4). The results of previous photo-elastic investigations are applied to test-pieces for tensile tests, and some interesting observations on the distribution of stress are recorded.

J. J. Thomas and J. H. Nead, *Static and Dynamic Tension Tests on Nickel Steel* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921). Results are given of an investigation made to determine the relation between static and dynamic tensile tests as measured by the work required to break test-pieces slowly in a tensile testing machine, and rapidly by means of a falling weight.

K. Sipp, *Application of the Shear Test to Cast Iron* (Stahl und Eisen, December 23, 30, 1920, pp. 1697-1704). A new method of performing shear tests on cast iron consists in preparing short test-pieces of cylindrical form on which a collar of a specified size is turned. The test-piece is placed on a die into which the turned part loosely fits, the collar resting on the upper surface of the die-box. The specimen and die are placed under a plunger, which puts pressure on the upper end of the specimen till the collar is sheared off. Tensile tests on bars of the same material are made, and the ratio of tensile to shear resistance is used as the criterion of the material.

H. F. Moore, *Tests Support Theory of Fatigue* (Paper prepared under the auspices of the Engineering Foundation, National Research Council, New York: Iron Trade Review, March 31, 1921, vol. 68, pp. 895-897). The failure of metals from fatigue is indicated by a number of experiments to be due largely to growth of minute flaws and cracks.

H. M. Howe and E. C. Groesbeck, *Stresses Caused by Cold-Rolling* (Proceedings of the American Society of Testing Materials, 1920, vol. 20, Part II. pp. 31-37). Experiments were made with the object of studying the effect of reducing the thickness of metal sheets by using many light drafts as compared with a few heavy ones. Strips of common cold-rolled soft sheet steel were used, all being cut from the same sheet, with an initial thickness of 0.036 inch. They were ground to 0.035 inch and then rolled in pairs to 0.029 inch, using in some cases 6 heavy passes, in others 10 passes, and in still others 31 light passes. It was concluded that in reducing a pair of strips by a

given amount of cold-rolling the internal stress, as inferred from the convexity assumed by the strips, increases with the amount of reduction per pass. This is ascribed to skin friction of the rolls. As the rolling progresses, the rate of deflection decreases, perhaps because the progressive increase of the stiffness of the strip enables them better to resist the bending effect of the skin friction. The elongation is proportional to the reduction and independent of the number of passes.

A. Pomp, *Resistance of Metals and Alloys to Compression* (Zeitschrift des Vereines Deutscher Ingenieure, September 11, 1920, vol. 64, pp. 745-746). The comparative crushing resistance of steel and other metals has been studied. A specimen of steel with 0.06 carbon and one with 0.5 carbon were tested and compared with specimens, of the same size, of lead, copper, aluminium, and bronze. The steels were drawn and annealed, and the size of the test-pieces was 10 millimetres diameter by 20 high. The following results were obtained :

	Load. Tons.	Compression. Millimetres.
Steel, 0.5 carbon	14.5	11
Bronze, with 62 per cent. copper	14.5	11.5
Steel, 0.06 carbon	14.5	12.7
Copper	8	12
Aluminium	6.25	14
Lead	1	15

Curves are plotted showing the behaviour of the metals at all stages as the load was increased.

W. E. Dalby, *Elastic Properties and Plastic Extension of Metals* (Philosophical Transactions of the Royal Society, September 29, 1920, vol. 221, pp. 117-138). Iron or mild steel when overstrained will rapidly recover their elastic state when immersed in boiling water. High carbon and alloy steels will not recover from overstrain either by resting many months or by boiling. An overstrained 3 per cent. nickel steel will entirely recover its elasticity by reheating to 550° C. Other phenomena connected with the elastic properties of steel are discussed.

E. W. Kaiser, *Behaviour of Wrought Iron and Mild Steel under Sudden Stress at Low Temperatures* (Stahl und Eisen, March 10, 1921, vol. 41, pp. 333-337). Notched specimens of wrought iron and mild basic steel were prepared for impact test, and these were cooled down to temperatures below freezing point. The effect of cold is very marked both in wrought iron and steel, but much more so in the case of the steel. Mild steel when cooled to -20° C. lost about 85.5 per cent. of its notch toughness at 15°. Wrought iron, on the other hand, lost 42.3 per cent. of its original notch toughness when tested at -20° C.

P. Chevenard, *Torsional Elasticity of Nickel Steel containing a High Percentage of Chromium* (Comptes Rendus, July 12, 1920, vol. 171, pp.

93-96). Three series of nickel-chromium iron alloys were examined, containing 5, 10, and 15 per cent. chromium respectively, with 1.2 per cent. manganese in the 15 per cent. chromium material. For the alloy with 39.2 per cent. nickel and 10 per cent. chromium, the torsional modulus remains practically constant up to 180° C. In the region of 12 per cent. chromium, the elasticity is perfectly constant over a wide temperature range. As the chromium is increased the temperature rises, at which a rapid falling off of the elasticity sets in, and at 15 per cent. chromium the temperature at which the elasticity drops is 405° C.

H. Bonte, *Tensile Properties of Iron and Steel Material* (Zeitschrift des Vereines Deutscher Ingenieure, December 18, 1920, vol. 64, pp. 1071-1073).

The Yield Point (Engineer, January 28, 1921, vol. 131, p. 90). Though the revision of tensile tests has long been in progress, the terms used to describe the results of an ordinary tensile test are still unaltered. This criticism applies most strongly to the term "yield point" or "yield stress," which is sometimes loosely identified with the "elastic limit." The British Engineering Standards Association is endeavouring to avoid vagueness by introducing into its specifications a new and more rational term in place of the discredited "yield." The new term is "proof stress," which for specification purposes is defined as a stress which the test-piece must withstand without showing an appreciable amount of permanent extension after removal of the stress. An "appreciable" extension is defined as not more than one-half of 1 per cent. of the gauge length of the test-piece.

H. Rudeloff, *Influence of the Method of Riveting on the Stresses and Tensile Properties of the Rivet* (Mitteilungen aus dem Materialprüfungsamt zu Berlin-Lichterfelde, 1915, vol. 33, No. 2, pp. 81-113). A study of the effect of press riveting, pneumatic, and hand riveting on the tensile stresses in rivets of different lengths. A full report of the investigation has already been published (Carnegie Scholarship Memoirs, 1914, vol. 6, pp. 170-215).

E. P. and E. H. Stenger, *Fatigue of Spring Steel* (Metallurgical and Chemical Engineering, September 29, 1920, p. 356).

H. Kempton Dyson, *High Tension Steel Concrete Bars* (Paper read before the Concrete Institute, January 13, 1921 : Iron and Coal Trades Review, January 21, 1921, vol. 102, p. 90). An account is given of a number of tests carried out on steel bars in reinforced concrete.

Radiography of Metals.—A. P. M. Fleming and J. R. Clarke, *Radiology Applied to the Testing of Material* (Paper before the Manchester Association of Engineers : Engineering, December 24, 31, 1920, vol. 110, pp. 850-852, 877-879). The paper contains a general survey of the extent to which radiology can be used in the testing of materials ; the limitations of the method are indicated and possible lines of advancement are suggested.

Steels for Special Purposes.—L. Aitchison, *Modern Automobile Steels* (Journal of the Birmingham Metallurgical Society, 1919, vol. 7, Part XIII. pp. 511–531). The main requirements for automobile steels are—high strength, high toughness, great durability, ease of machining, ease of heat treatment, constancy, and homogeneity of properties. A classification of automobile steels and alloy steels is given, with their corresponding composition, tensile properties, and mode of heat treatment. The alloy steels most suitable for valves, valve springs, and ball-bearings are enumerated.

G. Gabriel, *Steel for Valves of Combustion Motors* (Technique Automobile et Aérienne: Iron Age, November 11, December 2, 1920, vol. 106, pp. 1249–1251, 1465–1469). The various valve troubles are classified, and the properties of tungsten, chrome, and nickel steels suitable for valves are discussed.

W. H. Hatfield, *Steel from the Standpoint of Marine Engineering* (Journal of the West of Scotland Iron and Steel Institute, February 1921, vol. 28, pp. 52–72). The author surveys the properties and conditions of the various kinds of steel used in ship construction and marine engineering. He recommends the use, wherever possible, of steel of increased mechanical strength for ship plates and sections; the extension of the use of some of the special steels now available for transmission parts; and the use of other special steels capable of resisting rust and the effect of high temperatures.

Failures and Defects of Materials.—*Failure of Metals under Internal and Prolonged Stress.* On April 6, 1921, a general discussion on this subject was held under the conjoint auspices of the Iron and Steel Institute, the Institution of Mechanical Engineers, the Faraday Society, the Institute of Metals, the North East Coast Institution of Engineers and Shipbuilders, the West of Scotland Iron and Steel Institute, and the Institution of Engineers and Shipbuilders in Scotland. Discussion was initiated by an introductory address by W. Rosenhain, giving a general survey of the subject, followed by a series of papers, which included the following:

C. H. Desch, “Chemical Influences in the Failure of Metals under Stress.”

W. H. Hatfield, “Mechanism of Failure in Metals from Internal Stress.”

J. C. W. Humfrey, “Internal Stresses in Relation to Microstructure.”

F. Rogers, “Effects of Prolonged Stress on Metals at High Temperatures.”

Sir H. Fowler, “Notes on Fractures in Locomotive Boiler Tubes.”

D. Hanson, “Intercrystalline Failure in Steel.”

J. A. Jones, “Intercrystalline Cracking of Mild Steel in Salt Solution.”

H. S. Rawdon, “The Presence of Internal Fractures in Steel

Rails and their Relation to the Behaviour of the Material under Service Stresses."

An account of the proceedings together with abstracts of the above papers are given in *Iron and Coal Trades Review*, April 8, 15, 1921, vol. 102, pp. 502-506, 523-524.

J. H. Andrew, *Defects in Steel and Their Detection* (Journal of the West of Scotland Iron and Steel Institute, 1920-21, vol. 28, pp. 28-31). The methods employed for the detection of defects in steel are summarised under the several headings of micro-examination, macro-printing, the taking of recalescence curves, the determination of dilatation, the measurement of the resistivity, and the testing of the magnetic properties. The procedure in carrying out all these methods is described.

C. Frémont, *Origin of Cracks in Axles* (Comptes Rendus, May 1920, vol. 170, pp. 1161-1164). In the case of axles which rotate, when the stresses set up by shocks exceed the elastic limit, cold-work is performed on the material which in time produces creeping fracture circumferentially. In the case of fixed axles, cracks parallel with the diameter start from the upper and lower surfaces simultaneously.

J. E. Howard, *Shattered Zones in Certain Steel Rails* (Proceedings of the American Society for Testing Materials, 1920, vol. 20, Part II, pp. 44-59). The nature and causes of shattered zones found occasionally in steel rails have been studied, and the result of observations is summed up as follows: Shattered zones are interior manifestations, being surrounded with walls of unshattered metal. The shattering cracks in rails occur along the middle of the head and at the junction of the web and base. The cracks are of appreciable size and contain no foreign inclusions. They sometimes follow grain boundaries, and sometimes pass through the grains themselves. They are not associated with other defects, nor peculiar to segregated areas, but are prevalent in the harder grades of steel, and so far have not been observed in the softer grades. The shattering cracks appear to be of thermal origin; that is, they are cooling or shrinkage cracks, acquired presumably after the last pass in the rolling-mill. The hot-sawed ends of rails have been found unshattered. The cracks occupy zones in the section of the rails which upon cooling acquire a state of initial tension, and have not been found in those parts which are left in a final state of compression. In steel tires the disposition, size, and orientation of the cracks are even more suggestive of a thermal origin than those in rails. It is thought that, as shattered metal occurs in many rails which display transverse fissures, the elimination of the shattered zone would arrest the development of transverse fissures.

E. H. Schulz and J. Goebel, *Flaky Fracture in Steel* (Stahl und Eisen, November 4, 1920, vol. 40, pp. 1479-1485). Woody or flaky fracture are attributed to several quite different causes. Two chief kinds of flaky fracture may be distinguished: one due to flaws

raising from piping, inclusions, blowholes, slag threads, and segregations, which produce spots of local weakness; the other is not yet fully explained but is apparently connected in some way with internal stresses.

A. E. White, *Constitution and Properties of Boiler Tubes* (Mechanical Engineering, November 1920, vol. 42, pp. 603–606). The causes of defects in tubes are discussed, among them being grain growth due to heating to temperatures below the critical point. Brittleness may result from absorption by the metal of hydrogen, attributable to faulty feed-water treatment.

Specifications and Standardisation of Materials.—H. Brearley, *Impurities in Steel* (Engineer, October 15, 1920, vol. 130, pp. 375–376). In discussing the reasons for or against the retention of low sulphur and phosphorus limits in the B.E.S.A. specifications for railway material, it is pointed out that there is no evidence of a metallurgical kind to warrant the adoption of the 0·035 per cent. limit or the substitution of an 0·05 limit for sulphur and phosphorus. The chemical clauses in a complete specification do not ensure the quality of the finished product. Detailed mechanical tests and omnibus tests fail to distinguish tires, axles, or springs containing 0·03 per cent. sulphur and phosphorus from those containing 0·05 per cent., and material with up to 0·07 per cent. phosphorus has been known to give as good results as that averaging 0·03 sulphur and phosphorus. It is advocated that material which has been in service on railways for twenty to forty years should be examined, and official records of their composition be prepared which might serve as a valid test of the trustworthiness of less pure material.

E. A. Wraight, *Standardisation of Materials Employed in Mining and Milling Plant* (Institution of Mining and Metallurgy, Bulletin No. 196, January 1921, pp. 1–18). The author summarises very briefly a report issued in 1912 by the South African Mines Trials Committee, which contained the results of an investigation by Robert Allen on various kinds of rock-drill steel. After testing thirty-eight steels, Allen concluded that there was no practical difference in open-hearth, Swedish Bessemer, electric or crucible steels, provided the composition was the same. The most satisfactory composition he found to be—Carbon, 0·65 to 0·75; silicon, 0·05 to 0·15; sulphur and phosphorus, together not over 0·035; manganese, 0·25 to 0·35 per cent. The author then states the requirements which drill steel should fulfil, and gives the composition of drill steel according to American, Sheffield, and German specifications, which he criticises. With regard to the formation of the hole in the drill, it is stated that the bulk of the hollow drill steel imported into this country is probably mandrel-rolled, whereas English-made drills are usually core-rolled. The latter method is less likely to cause surface cracks in the interior of the central hole.

R. T. Rolfe, *The Mechanical Qualities required in Eyebolts: with Some Consideration of the Izod Test, in its Relation to Brittleness in Mild Steel* (Paper read before the Institution of Mechanical Engineers, February 1921). Conditions specifying the requirements of material for eyebolts are laid down, the composition of the steel being also stated.

B. Schulz, *Standard Specifications for Metals* (Elektrotechnische Zeitschrift, 1920, vol. 41, pp. 213-214). The author reviews the progress made in Germany towards standardisation of metals and alloys.

Magnetic Properties.—S. Evershed, *Permanent Magnets in Theory and Practice* (Journal of the Institution of Electrical Engineers, September 1920, vol. 58, pp. 780-837). The paper contains an account of the theory of permanent magnetism which combines Ampère's hypothesis of molecular currents with Ewing's theory of the interactions between the magnetic molecules. The elementary principle on which the predetermination of permanent magnets depends is derived from the simple proportionality between magnetomotive force and magnetic induction. Two fundamental equations are established for the case of magnets of uniform flux density, the first being a statement of the law of maximum external energy which underlies economic design. Ordinary magnets of uniform sectional area are then dealt with, and the author's alternative methods of forecasting the energy output of permanent magnets are described.

K. Honda and S. Saito, *K.S. Magnet Steel* (Proceedings of the Physical and Mathematical Society of Japan, 1920, vol. 2, pp. 32-38). The alloy is a special steel containing cobalt, 30 to 40 per cent.; tungsten, 5 to 9 per cent.; chromium, 1.5 to 3 per cent.; and carbon 0.4 to 0.8 per cent. The most suitable quenching temperature is 950° in a bath of heavy oil. The alloy requires practically no heat treatment in order to be used as a permanent magnet in electrical instruments.

Sir R. Hadfield, S. R. Williams, and I. S. Bowen, *The Magnetic Analysis of Manganese Steel* (Proceedings of the Royal Society, 1921, vol. 98, pp. 297-302). Tests were made on six manganese steel rods quenched in water, in the non-magnetic condition, and three were afterwards annealed, which rendered them magnetic. The steel contained 12.20 per cent. manganese. The changes in the length of the rods when subjected to magnetic fields were determined (Joule effect). In the rods in the magnetic condition the change was an increment for all field strengths. The non-magnetic specimens showed no change of length. The effect on the intensity of magnetisation when subjected to longitudinal stress was also investigated (Villari effect). For all field strengths the application of tensile stress increased the intensity of magnetisation of the magnetic specimens.

Gumlich, *Determination of the Magnetic Coercive Force and its Variation Due to Heat Treatment of the Iron* (Elektrotechnische Zeitschrift, October 7, 1920, p. 797). The application of the value of the

coercive force, as recommended by L. W. Wild (Electrician, 1920, vol. 84, p. 320), for the detection of changes in a material due to thermal or mechanical treatment, is discussed by the author. He points out that the method is not new and offers no advantages over the ballistic method.

Gumlich, *The Magnetic Properties of Iron-Nickel Alloys* (Elektrotechnische Zeitschrift, November 18, 1920, pp. 919-920). A general discussion of the magnetic properties of reversible and irreversible nickel alloys, with criticisms of a work of Yensen on the magnetisability of such alloys.

L. R. Ingersoll, *Physical Properties of Nickel-Iron Alloys* (Physical Review, August 1920, vol. 16, pp. 126-132). The specific heats, thermal conductivities, thermo-electric powers, and resistivities have been determined for a series of iron-nickel alloys of exceptional purity and of definite composition.

K. Honda and K. Kido, *Change of Length by Magnetisation in Iron-Nickel and Iron-Cobalt Alloys* (Tôhoku University Science Reports, June 1920, vol. 9, pp. 221-231).

A. Portevin, *Electrical Resistance of Nickel Steels* (Comptes Rendus, 1921, vol. 172, pp. 445-447). The conditions of annealing exercise a considerable effect on the electric resistance of nickel steels. In steels containing 0.3 to 0.8 per cent. carbon and 7 to 15 per cent. nickel the resistance varied by 10 to 40 per cent. according as the steel was heated to 1000° C. and cooled in four to five hours, or heated to 1300° and cooled down in three days.

T. Ishiware, *The Magnetic Determinations of the A, A₁, A₂, and A₃ Points in Steels containing up to 4.8 per Cent. of Carbon* (Proceedings of the Physical and Mathematical Society of Japan, 1920, vol. 2, p. 91).

E. D. Campbell, *Studies of the Constitution of Steel* (Proceedings of the National Academy of Science, U.S.A., 1919, vol. 5, pp. 426-427). The author discusses the solution theory of steel and the influence of changes in carbide concentration on the electrical resistivity.

New Magnetic Testing Apparatus (Iron Age, October 28, 1920, vol. 106, pp. 1125-1128). An illustrated description is given of an instrument known as the defectoscope and its application to the magnetic testing of steel.

Gases in Steel.—J. W. Donaldson, *Gases Occluded in Steel* (Transactions of the Faraday Society, 1920, vol. 15, Part III. pp. 238-244). A 3.37 per cent. nickel steel and three mild steels were used in the investigation. The results show that the volumes of the gases dissolved by the various steels are much higher than those dissolved by similar alloy steels of approximately the same carbon content and prepared by similar processes and undergoing the same treatment. They are also higher than volumes obtained by other investigators. The occluded gases are of a nature similar to those of other carbon steels which have been examined at various times. CO is present in small

quantities at low temperature, but increases as the temperature rises, attaining a maximum in each case between 670° and 700°. Hydrogen predominates at low temperatures, decreases to a minimum, then increases. Both gases are present in approximately equal proportions at high temperatures. The largest volumes of gas are evolved in the vicinity of the critical ranges, especially at the Ar₂ point.

O. A. Knight and H. B. Northrup, *Some Notes on the Effect of Nitrogen on Steel* (Chemical and Metallurgical Engineering, December 8, 1920, vol. 23, pp. 1107-1111). The investigation was carried out in order to determine the effect of ammonia on the microstructure and physical properties of steel, and its possible relation to the erosion of guns. An early part of the investigation consisted in heating steel wire tensile specimens in an atmosphere of ammonia at 650° C. for varying lengths of time at a pressure of about 840 millimetres mercury, and the subsequent heating of some of these specimens in hydrogen. The effect of heating in ammonia diminished the tensile strength and greatly reduced the elongation, while the reduction of area was rendered zero. The effect of ammonia on all the different grades of plain carbon steel, keeping all elements constant except the carbon and varying it from practically pure iron to hypereutectoid steels, was also studied.

H. E. Wheeler, *Nitrogen in Steel and the Erosion of Guns* (Paper read before the American Institute of Mining and Metallurgical Engineers, August 1920). A description of experiments carried out at Watertown Arsenal. The effect of nitrogen under pressure on steel containers of various compositions at a red heat, the effect of decomposing ammonia on various alloy steels, iron, and non-ferrous alloys, and a new theory of the erosion of guns were studied.

Metallography and Structure of Steel.—*Etching Reagents* (Chemical and Metallurgical Engineering, February 2, 1921, vol. 24, p. 207). A list is given of most of the common reagents used in the laboratories of the United States Bureau of Standards for etching various metals and alloys.

F. G. Allison and W. M. Rock, *Studies of the Macrostructure of Cast Steel* (Chemical and Metallurgical Engineering, September 1, 1920, vol. 23, pp. 383-389). The method of development of the macrostructure used is that due to Humfrey.

H. S. Rawdon, *Macroscopic Examination of Metals* (Chemical and Metallurgical Engineering, March 2, 1921, vol. 24, pp. 385-387; October 4, 1920, vol. 106, pp. 965-968). The author gives a list of the more commonly used etching reagents and outlines the nature of the defects which are revealed by macroscopic examination. The use of ammonium persulphate, a very strongly oxidising agent which readily decomposes when dissolved in water, is advocated as giving particularly noteworthy results in etching. The method and strength of solution best calculated to reveal structure are described. It is

rapid in action and hence can reveal features close to the surface which frequent etching with other etching solutions might result in removing.

H. S. Rawdon, *Preparation of Small Pieces for Microscopic Examination* (Chemical and Metallurgical Engineering, March 16, 1921, vol. 24, pp. 475-476).

G. F. Comstock, *Some Deep-Etching Experiments on New Steel Rails* (Chemical and Metallurgical Engineering, December 1, 1920, vol. 23, pp. 1081-1082). In the experiments the specimens chosen were rails made according to usual practice and more or less segregated, and titanium-treated rails having a uniform structure. The specimens were all boiled for several hours in strong hydrochloric acid, until their macrostructures were prominently developed. The homogeneous rails showed sections free from any pits or markings except the lines due to the rolling out of the original dendritic structure of the ingots. The ordinary segregated rails, however, showed numerous deep streaks or elongated pits that are due, not to any unsound or shattered condition of the steel, but merely to segregation of impurities, chiefly sulphur, which caused the metal in those streaks to dissolve faster. It is important that such segregated streaks should not be confused with cracks in the steel, yet the method of examination by deep etching gives the same indication for both kinds of defect.

H. S. Rawdon and S. Epstein, *Metallographic Features Revealed by the Deep Etching of Steel* (United States Bureau of Standards, 1920, Technologic Paper 156). The method of deep etching by means of concentrated acids has been examined in detail. The metallographic features of steel revealed by deep etching are of three general types: chemical inhomogeneity; mechanical non-uniformity, and physical discontinuities.

J. Mitchell, *The Metallography of Low Carbon Steels* (Journal of the West of Scotland Iron and Steel Institute, January 1921, vol. 28, pp. 38-49). The author discusses certain specific features of low carbon steel microstructures in so far as the interpretation of these reflects on the behaviour of the steel during use.

T. Turner, *Carbon in Iron and Steel* (Paper read before the Institution of British Foundrymen, March 15, 1921; Foundry Trade Journal, April 14, 1921, vol. 23, pp. 344-345).

S. Saito, *On the State of Carbide in Carbon Steels Quenched and Tempered* (Science Reports of the Tôhoku Imperial University, August 1920, vol. 9, No. 4, pp. 281-287).

C. M. Johnson, *Properties and Microstructure of Heat-Treated Non-Magnetic, Flame-Acid, and Rust-Resisting Steel* (Paper read before the American Society for Steel Treating, September 1920). A new alloy steel, the composition of which is not stated, compares favourably with other known alloys as regards acid-resisting and mechanical properties.

E. Maurer, *Beta-Iron and the Theories of Hardening* (Mitteilungen 1921—i.

aus dem Kaiser-Wilhelm Institut für Eisenforschung, 1920, vol. 1, pp. 39-86).

J. Alexander, *Colloidal State in Metals and Alloys* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1920).

O. R. Foster, *Some Remarkable Models of Atomic and Molecular Structure* (Chemical and Metallurgical Engineering, October 6, 1920, vol. 23, pp. 690-692). An illustrated description of the models prepared by L. Lefferts, which are plaster of Paris spheres, representing electrons and electron aggregates which are supported by wires and geometrically arranged in accordance with Langmuir's postulates.

Z. Jefferies and R. S. Archer, *Atoms and Metals* (Chemical and Metallurgical Engineering; March 23, 1921, vol. 24, pp. 507-512). A summary outline is given of the modern views of the ultimate constitution of matter, and the nature of forces existing between atoms in gas, liquid, and crystalline or amorphous solid as affecting the commonly measured physical properties of metals.

H. G. Carter, *Dendritic Steel* (Transactions of the American Society for Steel Treating, October 1920, vol. 1, pp. 56-61). The conditions favouring the formation of dendrites and dendritic structures are discussed. The hot stripping of steel castings should be carefully avoided as the steel becomes dendritic and the structure does not afterwards respond satisfactorily to heat treatment.

J. F. Adams, *Finishing Metallurgical Specimens* (Iron Trade Review, January 20, 1921, vol. 68, pp. 226-227). A description is given of the operations involved in the preparation of specimens.

C. Y. Clayton, *Polishing Motor for Metal Sections* (Chemical and Metallurgical Engineering, February 23, 1921, vol. 24, p. 356). A brief illustrated description is given of a motor which operates at 3000 revolutions per minute, and polishes even soft metals with complete satisfaction.

Properties of Alloy Steels and Alloy Metals.—C. E. Guillaume, *The Anomaly of the Nickel Steels* (Proceedings of the Physical Society, August 1920, vol. 32, pp. 374-404). The author presents a study of the physical properties of nickel steels, including magnetic properties, volume changes, both reversible and irreversible, the effect of additions of other elements, and the elastic properties. Some applications of invar are also dealt with.

C. E. Guillaume, *The Instability of Nickel Steels* (Comptes Rendus, November 29, 1920, pp. 1039-1041). The cause of the instability of nickel steels, as indicated by the variation in the rate of expansion during heating, is due to the transformations produced in the cementite (Fe_3C). By the creation of more stable carbides through adding chromium, tungsten, or vanadium, the changes in the cementite are suppressed and complete stability is reached.

P. D. Merica, *Iron-Nickel Alloys* (Chemical and Metallurgical

Engineering, March 2, 1921, vol. 24, pp. 375-378). A brief description of the properties of nickel steels and high nickel-iron alloys.

W. v. Selve, *Nickel* (Giesserei Zeitung, September 1, 15, 1920, vol. 17, pp. 277-282, 291-295). A review of the metallurgy of nickel, including the extraction of the metal, its microstructure, and its importance as an alloy metal.

J. Arnott, *Monel Metal* (Journal of the Institute of Metals, 1920, No. 1, vol. 23, pp. 545-551). The composition and properties of Monel metal are described, and the results of mechanical tests of the alloy in different states of heat treatment are given.

J. A. Mathews, *Molybdenum Steels* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1921). The developments in the manufacture and properties of molybdenum steels are briefly discussed.

G. W. Sargent, *Molybdenum as an Alloying Element in Structural Steels* (Proceedings of the American Society of Testing Materials, 1920, vol. 20, Part II, pp. 5-28). The composition and physical properties of molybdenum steel alloys for structural purposes are shown, and details of their manufacture are given. Molybdenum has also been introduced into cast iron with the result that the texture of the iron becomes finer and the toughness and tensile strength are increased.

Mechanical Properties of Molybdenum Steel (Zeitschrift für Metallkunde, January 1, 1921, vol. 13, pp. 30-32). Notes are given concerning the mechanical properties of molybdenum steels with varying percentages of molybdenum and chromium.

L. O. Hart, *Nickel-Chromium Alloys* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1920). The resistivity and thermo-electric properties of nickel-chromium alloys are discussed.

O. Ruff, *Alloys of Carbon, with Manganese, Nickel, Iron, Cobalt, and Chromium* (Forschungsarbeiten: Foundry Trade Journal, November 1920, vol. 22, p. 853). A short abstract is given of the results of experiments by the author and other collaborators.

Microstructure of Chromium Steels (Chemical and Metallurgical Engineering, April 20, 1921, vol. 24, pp. 703-706). A brief review of the work of previous investigators.

Recent Work on Chromium-Tungsten Steel, Methods of Magnetic Analysis (Chemical and Metallurgical Engineering, March 30, 1921, vol. 24, pp. 573-575). A series of articles reviewing the literature on chromium-tungsten steels, with special reference to the work of Honda and other Japanese investigators.

Structure of Tungsten Steels (Chemical and Metallurgical Engineering, April 27, 1921, vol. 24, pp. 745-748). A review of the work of Honda and Murakami on the structure and constitution of tungsten-iron-carbon alloys.

J. L. F. Vogel, *Metallurgy of Tungsten* (Paper before the British

Association, Cardiff meeting, 1920; Engineering, September 24, 1920, vol. 110, pp. 415-416).

C. H. Jones, *Manufacture of Tungsten* (Chemical and Metallurgical Engineering, January 7, 1920, vol. 22, pp. 9-16). The method of the Fan-steel Products Company, of Chicago, for the extraction of tungsten from its ores is described. The pure tungsten powder obtained is compressed into bars, which can be rolled hot and drawn into wire. The tensile strength of tungsten wire ranges up to 427 kilogramme-millimetres. A bibliography of literature on tungsten and its alloys is given.

Drawing of Tungsten Wire (Metall und Erz, October 22, 1920, vol. 17, pp. 449-452). The process of tungsten wire manufacture is described.

Influence of Copper on Steel.—D. M. Buck, *Development of Copper Steel* (Paper before the American Iron and Steel Institute, October 22, 1920; Blast-Furnace and Steel Plant, November 1920, vol. 8, p. 593). It is shown that copper additions to steel exercise a remarkable influence in checking corrosion, especially the attack of atmospheric moisture. The best results are obtained by alloying 0.15 to 0.30 per cent. of pure copper with Bessemer or open-hearth steel. Paint is also found to adhere better to copper steel than to ordinary steel. Perfect diffusion of the copper can readily be attained, and once diffused it does not segregate. A bibliography of the subject of copper steel is given.

Copper in Steel Tie-Plates reduces Corrosion (Engineering and Contracting, 1920, vol. 54, p. 256). The New York Central Railroad has found that by the addition of 0.25 per cent. of copper to mild Bessemer steel tie-plates the loss by corrosion is reduced from 5 to 6 per cent.

O. Bauer, *Corrosion Experiments with Steel Sheets containing Copper* (Stahl und Eisen, January 13, 20, 1921, vol. 41, pp. 37-45, 76-83). Experiments were made on Bessemer and open-hearth sheets containing 0.10 to 0.35 per cent. of copper. The results show that copper has considerable protective effect against acid attack, but exercises no noticeable influence in the case of exposure to sea-water and to distilled water, or of plates buried in the ground or exposed to atmospheric conditions.

E. A. Richardson and L. T. Richardson, *Influence of Copper on some Physical Properties of Iron and Steel* (Chemical and Metallurgical Engineering, March 20, 1921, vol. 24, pp. 565-567). Forging, filing, grinding, chiselling, and bending tests were carried out. It was found that copper added to iron produces red-shortness over a certain temperature range. The degree of brittleness and the temperature over which it occurs increase with an increase of copper content. It is believed that this brittleness is due to an intergranular film of copper or an alloy or compound of copper. The red-shortness is removed by the addition of manganese or chromium. This explains why copper

added to iron causes red-shortness, while it does not cause red-shortness in steel unless added in excessive amounts. The addition of copper up to at least 3.50 per cent. apparently does not impair the cold-working properties of the alloys. Beyond 2 per cent. of manganese the alloys become too brittle to work, while with more than 2 per cent. chromium the alloys become hard and tough.

Corrosion.—G. Paris, *Cause of Corrosion in Steam Boilers* (Revue Générale d'Electricité, February 5, 1921, vol. 9, pp. 182–185). The author shows that the gases held in solution in the water and not the salts are the real cause of internal corrosion in boilers. The complete removal of the dissolved oxygen from the feed water checks the corrosive action of both CO_2 and the dissolved salts.

I. D. N. Perdrizet, *Kestner's Apparatus for Removing Gases from Feed Water* (*Ibid.*, pp. 185–187). The apparatus consists of a sheet metal circular vessel in which are placed perforated cylinders containing prepared iron turnings. The boiler feed water is passed through the vessel, the direction of flow being reversed every twenty-four hours.

G. Stauch, *Ships and the Corrosion Menace* (Elektrotechnische Zeitschrift, 1920, vol. 41, p. 202). The author reviews the various methods that have been put into practice for the protection of ship plates, propellers, condenser tubes, and other parts from corrosion.

F. N. Speller, *Abatement of Corrosion in Central Heating Systems* (United States Bureau of Mines, 1919, Technical Paper, No. 236). The author reviews the methods in general use for the prevention of corrosion in central heating systems, and outlines the modern theory of corrosion.

At the general meeting of the American Electrochemical Society, April 1921, a symposium was held on corrosion, and the following papers were presented dealing with the corrosion and preservation of iron and steel:

W. H. Walker, "Introduction to Symposium on Corrosion of Iron and Steel."

O. W. Storey, "The Corrosion of Steel Ranges."

F. N. Speller, "Practical Means of Preventing Corrosion of Iron and Steel where not Exposed Directly to the Atmosphere."

D. M. Buck, "Some Observations on the Mechanism of the Increased Corrosion Resistance of Steel and Iron due to Small Copper Contents."

E. A. Richardson and L. T. Richardson, "The Corrosion of Old Iron."

O. P. Watts, "Principles of Alloying to Resist Corrosion."

H. A. Gardner, "Metal Protective Paints."

O. P. Watts and H. C. Knapp, "The Effect of Copper and Silver Salts on the Corrosion of Iron by Acids."

W. D. Richardson, "The Gap between Theory and Practice in the Production of Corrosion-Resisting Iron and Steel."

J. A. Aupperle and D. M. Strickland, "Observations on the Corrosion of Iron and Steel."

A. S. Cushman and G. W. Coggeshall, "Anomalies Encountered in a Study of Immersion Tests of Iron and Steel."

B. G. Worth, "Unusual Boiler Tube Corrosion by Carbon Dioxide."

T. S. Fuller, "Experiments on the Corrosion of Iron and Steel."

J. F. Thompson, "A Practical Aspect of the Corrosion Problem."

W. D. Richardson, *Rates of Solution of Iron and Steel in Non-Oxidising and Oxidising Acids* (Paper read before the American Institute of Chemical Engineers, 1920). Relatively pure iron dissolves at a low rate in non-oxidising acids such as normal H_2SO_4 (and HCl), whereas less pure metals, such as cast iron and malleable iron, dissolve at a relatively high rate, while cast steel dissolves at a rate between the two.

Rust-Resisting Steel.—*Krupp's Rustless Steels* (Krupp'sche Monatshefte, August 1920; Technical Review, November 30, 1920, vol. 7, p. 284). It is reported that Krupp's have lately introduced some special types of high nickel-chrome non-rusting steels, their resistance to attack depending on certain methods of heat-treatment. Comparative corrosion tests with Krupp's steels and other alloy steels were made, the results showing a remarkable resistance of the former to sea-water and acid attack as compared with ordinary nickel steels.

Electro-Deposition of Iron.—W. E. Hughes, *The Industrial Future of Electro-Deposited Iron* (Electrician, November 5, 1920, vol. 85, pp. 530-532). The scientific control of deposition as distinct from the mere fact of such deposition is exceedingly important, as the nature of the deposit depends for its value on the care with which it has been effected. The differences in structure when acid and neutral solutions are employed are shown by photomicrographs, and the relative merits with chloride and sulphate bars are compared. The present position of research work in Great Britain is also briefly noted.

W. A. Noyes, jun., *Some Aspects of Electrolytic Iron* (Paper read before the American Electrochemical Society, April 1921). The author has carried out experiments the object of which was to measure the minimum potential at which the electrolytic deposition of iron could be carried out.

T. S. Fuller, *Penetration of Iron by Hydrogen* (General Electric Review, August 1920, vol. 23, pp. 702-711). An investigation has been made of the effects of the absorption of hydrogen by iron at the kathode during electroplating, which has been found to cause brittleness in the metal. The penetration of hydrogen is much more rapid using a solution of 1 per cent. sulphuric acid than when similar solutions of potassium sulphate and of sodium hydroxide are used. Temperature also has a marked influence on the rate of absorption.

CHEMICAL ANALYSIS.

Analysis of Iron and Steel.—C. O. Bannister, *The Analysis of Special Steels* (Electrician, November 5, 1920, vol. 85, pp. 535–538). The use of electrometric titration methods and the application of the hydrogen electrode as a means of chemical and physico-chemical research are described, together with methods for the determination by electrometry of manganese, chromium, and vanadium.

J. R. Cain and L. C. Maxwell, *Electrolytic Resistance Method for Determining Carbon in Steel* (United States Bureau of Standards, Technologic Paper 141). The purpose of this study was to investigate the accuracy, speed, and practicability of a method for determining carbon in steel, dependent in principle on passing the carbon dioxide produced by direct combustion of the metal into a solution of barium hydroxide of known electrical resistance. After complete absorption of this gas the resistance is again determined, and from the increase (due to precipitation of barium ions) the percentage of carbon is deduced.

A. Cartoceti, *Estimation of Sulphur in Wrought Iron, Steel, and Cast Iron* (Giornale di Chimica Industriale ed Applicata, 1920, vol. 2, pp. 682–686. See Journal of Society of Chemical Industry, March 31, 1921, vol. 40, p. 181A). A method is recommended for checking the more rapid methods used in works laboratories for estimating sulphur in steel.

P. Oberhoffer and A. Knipping, *An Investigation of Baumann's Method of Determining Sulphur, with Notes on the Behaviour of Phosphorus in Iron* (Stahl und Eisen, February 24, 1921, vol. 41, pp. 253–258).

N. D. Ridsdale, *Phosphorus in Hæmatite Iron: Its Exact Determination and Commercial Importance* (Chemical News, 1920, vol. 120, pp. 219–221).

M. B. Danheiser, *A Rapid Qualitative Method for Nickel in Steel* (Chemical and Metallurgical Engineering, October 20, 1920, vol. 68, p. 770).

E. Jaboulay, *Determination of Vanadium in Steel* (Revue de Métallurgie, September 1920, vol. 17, pp. 627–629). A rapid and accurate method for the determination of vanadium is described.

C. O. Bannister, *Chemical Standard Samples* (Journal of the Society of Chemical Industry, 1920, vol. 39, pp. 351–352-R). The need of suitable chemical standards, especially in iron and steel analysis, is

pointed out, and an outline is given of the work already carried out in preparing such standards in this country and in the United States.

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HULTGREN, A. "*A Metallographic Study of Tungsten Steels.*" 8vo, pp. vi-95.
New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd.
1920.

[The author's study does not include high-speed steel or other quaternary steels containing tungsten, but only ternary tungsten steels. The investigation is limited to a few tungsten steels which were subjected to microscopic examination after different heat treatments, with the object of ascertaining the nature of the lowering or splitting of the point A₁, and the cooling from high temperatures. Also different free carbides were observed in these steels, for the closer study of which other tungsten steels and iron-tungsten-carbon alloys were investigated. On the data obtained an endeavour has been made to base a tentative iron-tungsten-carbon equilibrium diagram. The whole subject is therefore divided into a study of the transformations of tungsten steels under different heat treatments and the structures thereby formed, and a study of the carbides in tungsten steels.

As an introduction to each section a review is presented of the work of previous investigators, and the author's conclusions appear in many respects to be contrary to those hitherto generally accepted. This notwithstanding, a large amount of new information has been accumulated, and the work forms a valuable contribution to the existing knowledge of the constitution of tungsten steel alloys.]

JOHNSON, C. M. "*Rapid Methods for the Chemical Analysis of Special Steels, Steel-making Alloys, their Ores and Graphites.*" 8vo, pp. vii-541. Third edition, revised and enlarged. New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd. 1920.

[In presenting the third edition of his work, the author begins by emphasising the rule which, in his opinion, should serve as a guide to all who wish to experiment in the alloying of iron with other elements. His generalisation is expressed as follows: If iron be combined by fusion with notable quantities of an element whose melting point is very much below that of iron, the tendency is to produce a metal of inferior physical properties, but if iron be combined with an element whose melting point is nearly the same or higher than that of iron, then the tendency is to produce a metal of superior physical properties.

The new edition contains many new features in the form of improved tests for constituents of alloys and analytical methods, and the whole work forms an indispensable handbook for the steelworks chemist.]

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